An Evaluation of the Effectiveness of Polyelectrolyte Coagulant Aids for the Removal of Radioactive Isotopes by Water Treatment Processes

By

SIDNEY ALLISON HANNAH

A DISSERTATION PRESENTED TO THE GRADUATE COUNCIL OF
THE UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA
December, 1962

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to his committee chairman, Dr. A. P. Black, and to Professor F. W. Gilcreas, co-sponsor of the investigation, for their guidance and assistance. Special thanks are also due the other members of his supervisory committee, Dr. W. S. Brey, Dr. J. M. Pearce, and Dr. H. E. Schweyer.

The author is very grateful to Mr. A. C. Printz, Jr., Professor G. B. Morgan, and the staff of the Phelps Sanitary Research Laboratory for their valuable assistance.

Gratitude is also expressed to the Office of Civil and Defense Mobilization whose financial support made this project possible.

TABLE OF CONTENTS

Page

ACKNOWLEDGMENTS.. ii

LIST OF TABLES.. iv

LIST OF FIGURES.. vi

CHAPTER

I. INTRODUCTION.. 1

II. DECONTAMINATION OF WATER.. 4

III. POLYELECTROLYTES.. 12

IV. EXPERIMENTAL MATERIALS AND PROCEDURES.. 20

V. DISCUSSION OF RESULTS.. 27

VI. CONCLUSIONS.. 42

APPENDICES

I. ABBREVIATIONS USED IN TABLES AND FIGURES.. 46

II. TABLES.. 47

III. FIGURES.. 92

LIST OF REFERENCES.. 124

BIOGRAPHICAL SKETCH.. 130

LIST OF TABLES

Table Page

1. CHARACTERISTICS OF SELECTED RADIOISOTOPES............. 3

2. CHEMICAL ANALYSES OF WATERS........................... 23

3. SORPTION OF Cs^{137} FROM TAP WATER BY VARIABLE DOSAGES OF CLAY.. 48

4. THE EFFECT OF pH ON SORPTION OF Cs^{137} FROM TAP WATER BY KAOLINITE AND VOLCLAY............................... 49

5. THE EFFECT OF VARIABLE DOSAGES OF LIME ON REMOVAL OF Cs^{137} FROM TAP WATER WITH 1000 ppm ILLITE AND 25 ppm FERRIC SULFATE.. 50

6. REMOVAL OF Sr^{89} FROM WELL WATER WITH 188 ppm LIME, 35 ppm SODA ASH, AND DIS-106........................... 51

7. REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY AND VARIABLE DOSAGES OF COAGULANT AIDS................. 52

8. REMOVAL OF Sr^{89} FROM WELL WATER WITH LIME, SODA ASH, AND VARIABLE DOSAGES OF CLAYS.......................... 55

9. REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY AND VARIABLE DOSAGES OF LIME, SODA ASH, AND DIS-106.... 57

10. REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY, 202 ppm LIME, 45 ppm SODA ASH, AND VARIABLE DOSAGES OF N17.. 58

11. REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY, 202 ppm LIME, 45 ppm SODA ASH, AND VARIABLE DOSAGES OF W... 59

12. REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY, 202 ppm LIME, 200 ppm SODA ASH, 10 ppm STABLE Sr, AND VARIABLE DOSAGES OF N17.............................. 60

13. REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY, EXCESS LIME (402 ppm), EQUIVALENT SODA ASH (326 ppm), 10 ppm STABLE Sr, AND VARIABLE DOSAGES OF N17.......... 61

Table Page

14. REMOVAL OF Pm^{147} FROM TAP WATER WITH 60 ppm ALUM OR 36 ppm FERRIC SULFATE AND VARIABLE DOSAGES OF COAGULANT AIDS.. 62

15. REMOVAL OF Pm^{147} FROM WELL WATER WITH VARIABLE DOSAGES OF CLAYS.. 66

16. REMOVAL OF Pm^{147} FROM WELL WATER WITH VARIABLE DOSAGES OF LIME AND SODA ASH...................................... 67

17. REMOVAL OF Pm^{147} FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, AND VARIABLE DOSAGES OF COAGULANT AIDS.. 68

18. REMOVAL OF Pm^{147} FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, 500 ppm CLAY, AND VARIABLE DOSAGES OF COAGULANT AIDS... 71

19. REMOVAL OF I^{131} FROM WELL WATER WITH 100 ppm ACTIVATED CARBON, CHLORINE, AND VARIABLE DOSAGES OF ALUM OR FERRIC SULFATE.. 72

20. REMOVAL OF I^{131} FROM WELL WATER WITH 100 ppm AQUA NUCHAR A, CHLORINE, AND VARIABLE DOSAGES OF COAGULANT AIDS.. 73

21. COAGULATION OF CONCENTRATED URANIUM SOLUTION WITH LIME AND ALUM.. 74

22. COAGULATION OF CONCENTRATED URANIUM SOLUTION WITH LIME AND FERRIC SULFATE...................................... 75

23. REMOVAL OF URANIUM FROM WELL WATER WITH 30 ppm ALUM, KAOLINITE, AND COAGULANT AIDS............................. 76

24. REMOVAL OF URANIUM FROM WELL WATER WITH 25 ppm FERRIC SULFATE, KAOLINITE, AND COAGULANT AIDS................... 78

25. REMOVAL OF URANIUM FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, KAOLINITE, AND COAGULANT AIDS........... 80

26. SUMMARY OF TURBIDITY REDUCTION WITH COAGULANT AIDS....... 82

27. SUMMARY OF ACTIVITY REMOVAL WITH COAGULANT AIDS.......... 87

LIST OF FIGURES

Figure Page

1. SORPTION OF Cs^{137} FROM TAP WATER BY VARIABLE DOSAGES OF CLAY.......... 93

2. THE EFFECT OF pH ON SORPTION OF Cs^{137} FROM TAP WATER BY 1000 ppm FULLERS EARTH OR 1000 ppm ILLITE.......... 94

3. REMOVAL OF Cs^{137} FROM TAP WATER BY 1000 ppm FULLERS EARTH OR ILLITE WITH VARIABLE DOSAGES OF N17.......... 95

4. REMOVAL OF Cs^{137} FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, 1000 ppm FULLERS EARTH OR ILLITE, AND VARIABLE DOSAGES OF DIS-106.......... 96

5. REMOVAL OF Cs^{137} FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, 1000 ppm FULLERS EARTH OR ILLITE, AND VARIABLE DOSAGES OF "SiO_2".......... 97

6. REMOVAL OF Cs^{137} FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, 1000 ppm FULLERS EARTH OR ILLITE, AND VARIABLE DOSAGES OF CN.......... 98

7. REMOVAL OF Cs^{137} FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, 500 ppm FULLERS EARTH, 500 ppm ILLITE, AND VARIABLE DOSAGES OF CN.......... 99

8. THE EFFECT OF Mg ADDED AS $MgCl_2$ ON THE REMOVAL OF Cs^{137} FROM WELL WATER WITH LIME, SODA ASH, 500 ppm FULLERS EARTH, AND 500 ppm ILLITE.......... 100

9. THE EFFECT OF STABLE Cs ON THE REMOVAL OF Cs^{137} FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, AND 1000 ppm FULLERS EARTH OR 1000 ppm ILLITE.......... 101

10. THE EFFECT OF SODA ASH DOSAGE ON REMOVAL OF Sr^{89} FROM WELL WATER BY LIME-SODA SOFTENING.......... 102

11. REMOVAL OF Sr^{89} FROM WELL WATER WITH VARIABLE DOSAGES OF CLAY.......... 103

12. REMOVAL OF Pm^{147} FROM TAP WATER BY COAGULATION WITH VARIABLE DOSAGES OF ALUM OR FERRIC SULFATE.......... 104

Figure Page

13. THE EFFECT OF pH ON REMOVAL OF Pm^{147} FROM TAP WATER WITH 60 ppm ALUM OR 36 ppm FERRIC SULFATE........................ 105

14. REMOVAL OF Pm^{147} FROM WELL WATER WITH VARIABLE DOSAGES OF CLAYS.. 106

15. REMOVAL OF Pm^{147} FROM WELL WATER WITH 46 ppm SODA ASH AND VARIABLE DOSAGES OF LIME.................................. 107

16. REMOVAL OF Pm^{147} FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, AND VARIABLE DOSAGES OF ACTIVATED SILICA......... 108

17. REMOVAL OF Pm^{147} FROM WELL WATER WITH VARIABLE DOSAGES OF ACTIVATED CARBON.. 109

18. REMOVAL OF I^{131} FROM WELL WATER WITH VARIABLE DOSAGES OF ACTIVATED CARBON.. 110

19. REMOVAL OF I^{131} FROM WELL WATER WITH VARIABLE DOSAGES OF CHLORINE AND 50 ppm ALUM OR 40 ppm FERRIC SULFATE.......... 111

20. REMOVAL OF I^{131} FROM WELL WATER WITH VARIABLE DOSAGES OF CHLORINE AND 100 ppm C-190-N.............................. 112

21. REMOVAL OF I^{131} FROM WELL WATER WITH VARIABLE DOSAGES OF CHLORINE AND 100 ppm AQUA NUCHAR A........................ 113

22. REMOVAL OF I^{131} FROM WELL WATER WITH VARIABLE DOSAGES OF CHLORINE AND 1000 ppm AQUA NUCHAR A....................... 114

23. REMOVAL OF I^{131} FROM WELL WATER WITH 0.1 ppm CHLORINE AND VARIABLE DOSAGES OF AQUA NUCHAR A..................... 115

24. REMOVAL OF I^{131} FROM WELL WATER WITH 100 ppm AQUA NUCHAR A, 202 ppm LIME, 46 ppm SODA ASH, AND VARIABLE DOSAGES OF CHLORINE.. 116

25. THE EFFECT OF VARIABLE ACTIVITY ON REMOVAL OF I^{131} FROM WELL WATER WITH 0.1 ppm Cl_2 and 100 ppm AQUA NUCHAR A...... 117

26. THE EFFECT OF STABLE I^- ON REMOVAL OF I^{131} FROM WELL WATER WITH 0.1 ppm Cl_2 and 100 ppm AQUA NUCHAR A................ 118

27. THE EFFECT OF pH ON PRECIPITATION OF URANIUM WITH LIME AND SODIUM HYDROXIDE..................................... 119

28. COAGULATION OF DILUTE URANIUM SOLUTION WITH KAOLINITE AND ALUM OR FERRIC SULFATE................................ 120

Figure Page

29. REMOVAL OF URANIUM FROM DILUTE URANIUM SOLUTION WITH LIME AND KAOLINITE.. 121

30. REMOVAL OF URANIUM FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, 500 ppm KAOLINITE, AND KELGIN W.......... 122

31. REMOVAL OF URANIUM FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, 500 ppm KAOLINITE, AND ACTIVATED SILICA.. 123

I. INTRODUCTION

Radioactive contamination of our water supplies has increased in recent years, paralleling the advances in nuclear technology and the growing uses for radioisotopes. These radioactive materials constitute a serious health hazard if present in significant concentrations and make the water unfit for many industrial processes. The discharge of radioactive substances is presently regulated by laws designed to ensure the safety of water users but abnormal conditions may result in dangerous levels of activity in the watercourses. In wartime, the widespread use of nuclear weapons would certainly result in severe contamination. Conventional water treatment processes have removed varying amounts of contamination depending on treatment used, source and composition of the activity, and on other substances present in the water. The purpose of this investigation was to determine the possible benefits of polyelectrolytes as aids to the conventional and specially modified treatment processes in water decontamination.

The major sources of radioactive water contaminants include the fallout from nuclear weapons explosions, wastes from production of radioisotopes or recovery of reactor fuel elements, and wastes from individual users of isotopes. The chemical and physical properties of the contaminants determine the extent to which they may be removed from water by a selected process. These properties in turn depend on the source of the contamination.

Nuclear weapons detonated over land form melted silica spheres which are only sparingly soluble in the pH range of natural waters (1,2). Uranium mill wastes, containing the radioactive daughter products of uranium disintegrations, hold 99 per cent of the most dangerous radioisotope, Ra^{226}, in an insoluble form within the spent slimes and sands (3). On the other hand, the chemical wastes will generally contain the radioelements in a soluble ionic form. Smaller fallout particles, which deposit downwind from a nuclear blast, may have volatile fission products condensed on their surfaces and thus cause considerable water contamination by solution of the activity (4). For complete decontamination, both the soluble and the insoluble activity must be removed.

Specific radioelements which enter the body are selectively absorbed from the gastrointestinal tract and may then be generally distributed throughout the body fluids or may be concentrated in particular organs. The health hazard of a particular radioelement may be evaluated by considering the rate of absorption, the body distribution, the half life of the material, the nature and energy of the radiation, and the rate of excretion from the body. Maximum permissible concentrations (MPC) have been determined for many radioisotopes (5).

Five elements representing a potential hazard to water users were selected for removal studies with polyelectrolytes. Their characteristics are presented in Table 1. With the exception of Pm^{147}, all are difficult to remove by ordinary coagulation.

TABLE 1

CHARACTERISTICS OF SELECTED RADIOISOTOPES

Element	MPC(μC/ml)	Chemical Form	Critical Organ
Cs^{137}-Ba^{137m}	2×10^{-4}	CsCl in HCl	Total body
Pm^{147}	2×10^{-3}	$PmCl_3$ in HCl	Gastrointestinal Tract
Sr^{89}	1×10^{-4}	$SrCl_2$ in HCl	Bone
U^{238}	4×10^{-4}	$UO_2(NO_3)_2 \cdot 6\ H_2O$	Gastrointestinal Tract
I^{131}	2×10^{-5}	NaI in basic Na_2SO_3 soln.	Thyroid

II. DECONTAMINATION OF WATER

The radioactive elements present in fallout generally comprise less than one part per billion by weight of the total fallout (4). Much inactive material, consisting of weapon vehicle fragments and debris from the ground below the explosion, must be removed from the water in order to remove the activity. To be removed by conventional treatment processes, soluble activity must be precipitated or incorporated into another solid present in the water. The literature was reviewed to find the optimum conditions for decontamination.

Natural Decontamination

A number of natural processes serve to reduce the activity before the water reaches the treatment plant. Such processes include sedimentation, ion exchange and sorption by silts and clays, and biological concentration by organisms in the streams. These often afford only temporary storage for activity and may result in surges of activity when high flows resuspend the solids. Concentration of radioactivity by natural agents is reviewed in ORNL-2557 (6).

Removal by Water Treatment Processes

Only those procedures which are readily adaptable to existing treatment plants were studied with polyelectrolytes. These include ion exchange and sorption on solids, coagulation and precipitation, and lime-soda softening. Other processes such as distillation, evaporation, electrodialysis, electrolytic separation, solvent extraction, and freezeout have been studied by others for activity removal from wastes but they are impractical, at the present time, for treating the large volumes of water required for public consumption.

Ion Exchange and Sorption on Solids

Clays and Minerals. Clays and minerals, which form natural ion exchange systems, vary in their effectiveness for removing radioactivity from water. Some of the radioelements are held to the outside of the solid by surface valences while others penetrate the lattice and bond internally. The solids should be finely ground to increase the surface area and permit easier access to the interior.

Christenson *et al*. (7) found that celite, kaolin, tuff, and pumice would remove plutonium from laboratory wastes. Lacy (8) slurried a mixed clay (montmorillonite and kaolinite) with tap water containing radioisotopes and removed 84-95 per cent of Sr^{90}-Y^{90} but only 5 per cent of I^{131}. Other investigators (9-13) found that clays had a particularly strong affinity for cesium. Strontium was usually taken up to a lesser degree.

Foreign ions in solution interfere with removal of radioelements by competing for the available sorption sites. Calcium ion greatly depresses strontium uptake because of the chemical similarity of the two elements (10,13,14). Since hydrogen ions also depress uptake, best removal of activity generally occurs at high pH (8,9). Davey and Scott (15) showed that the presence of sulfate ion decreased the amount of uranium adsorbed on clay.

Extruded montmorillonite was found to be a good column adsorbent but many cations could be leached out of the clay by continued passage of water (16). A comparison of slurry and column treatments showed that a single slurry treatment reached only 50 per cent of the clay saturation value reached in a column for the same activity (13). The contact time between the water and the solid should be as long as practical since equilibrium is very slowly attained with some isotopes (8,12).

Straub et al. (17) and Eliassen et al. (18) used clay in conjunction with alum and ferric chloride or ferric sulfate for removal of activity. Other common minerals found to have adsorptive properties for radioisotopes are Florida pebble phosphate (19) and limestone (20). Robinson (21) has compiled a bibliography concerning ion exchange minerals and disposal of radioactive wastes.

Ion Exchange Resins. The ion exchange resins commonly used for water softening will also remove radioisotopes from water. Either cation exchange resins or anion exchange resins may be required depending on the ionic form of the activity. Friend (22) removed greater than 99 per cent of Sr^{89} and I^{131} from water with cation and anion exchange resins respectively and Downing et al. (23) removed greater than 97 per cent of Sr^{89} with synthetic resins and aluminosilicates.

It has been noted that activity continues to be removed by cation exchange resins long after their capacity for removing hardness has been exhausted (23,24) but resin capacity for cesium is only about half that for hardness. The water pH may affect activity removal by influencing solubility or uptake of ions. Interference due to complexing agents is reduced at low pH (25). Batch-type treatment with ion exchange resins was found to be less efficient than column-type operations but equilibrium was more readily accomplished (26).

Special Methods. Lauderdale and Emmons (27) succeeded in removing a mixed fission product from tap water by passing it through two glass columns containing steel wool, burnt clay, activated carbon, and mixed cation and anion exchange resins. Lacy (28) and Lauderdale (29) slurried waters containing radioisotopes with metal dusts and removed up to 99.9 per cent of the activity. Cs^{137} and I^{131} were not effectively removed by this process. Straub et al. (17) used activated carbon to remove I^{131}. Newell and Christenson (30) removed plutonium from laboratory and laundry wastes by adsorption on activated carbon, activated sludge, and trickling filter organisms.

Coagulation and Precipitation

Most coagulation studies have been carried out on radioactive wastes or on waters dosed with radioisotopes. With the exception of the cations above Periodic Group II, activity removals are usually poor with alum and iron salts unless supplementing procedures are used.

Christenson et al. (7), Newell and Christenson (30), and Pressman and Lindsten (31) used ferric chloride and lime to remove plutonium from water and also found alum to be effective but not as good as ferric chloride. Straub et al. (17) used alum and ferric chloride with clay and soda ash in jar tests to remove up to 98 per cent of rare earths but little Sr^{89} or I^{131}. Other investigators reported poor removals of strontium or iodine by coagulation (23,32,33,34). An overall removal of 70-73 per cent of mixed fission products, simulating radioactive constituents remaining one month after a nuclear explosion, was obtained by coagulation with alum, lime, and sodium silicate in a pilot plant (35).

Eliassen et al. (18) and Kaufman et al. (34) removed more than 99 per cent of P^{32}, as the orthophosphate anion ($PO_4^{\equiv}$), from water in coagulation tests with alum and ferric sulfate. The primary mechanism of removal was found to be simple counterion adsorption rather than isomorphous replacement in the floc structure. Much of the P^{32} initially removed was desorbed with time if the alum floc was allowed to age. Optimum removals of activity resulted under conditions of good coagulation as evidenced by the rapid formation of large, easily settleable flocs and optimum turbidity removals.

Burbank et al. (36) used alum and chlorinated copperas to remove radioactive particulate matter from water. Activity removal was maximum at the optimum pH of floc formation. A small amount of turbidity was necessary to serve as nuclei for floc formation but quantities over 10 ppm were of little significance in removing particulate matter.

Phosphate coagulation has removed nearly 98 per cent of radiostrontium from water (17,33,37). For best results with this method, the pH should be above 11.3 and the trisodium phosphate to lime ratio should exceed 2.2/1. The addition of stable strontium aids in precipitation of strontium phosphate (38).

Auxiliary procedures for decontamination of I^{131} have used $CuSO_4$, $AgNO_3$, and activated carbon with alum to remove up to 75 per cent of the activity (17). Carrier iodine with $AgNO_3$ precipitated nearly 96 per cent of the I^{131} (32). Sodium hypochlorite added before alum coagulation removed some I^{131} but this may have been due to volatilization (32).

Lauderdale and Eliassen (39) and Bell et al. (40) found lower removals of gross natural fallout activity in municipal water treatment plants than had been obtained in laboratory tests for removal of synthetic fallout products. There were extreme daily variations in activity removal but a trend toward decreasing percentage removals with increasing age of the fallout products was observed. Since the presence of turbidity, even in large amounts, had no apparent effect on decontamination, it was assumed that considerable self-purification had occurred during runoff and storage, leaving the most difficultly separable fraction behind. There were no significant differences in removal between the different conventional treatment processes. Over a period of time an average of 50-75 per cent activity removal may be expected (39).

Setter and Russell (41) removed 50-75 per cent of natural fallout products from rain, cistern, and surface waters by jar test coagulation. Junkins (42) reported removals of about 70 per cent of Columbia River activity by the Pasco, Washington, treatment plant.

Lime-Soda Ash Softening

With the exception of ion exchange, lime-soda ash softening is the only conventional water treatment process which gives high strontium removals. Most of the softening studies have, therefore, included this element.

Eliassen et al. (18) removed 74 per cent of Sr by lime-soda ash softening while Hoyt (43) removed 76 per cent of Sr with stoichiometric lime-soda ash dosages. Pressman and Lindsten (31) reported 97 per cent removal of Pu with the Army Mobile Water Purification Unit. Active phosphorus (P^{32}) was also removed during softening by precipitation as calcium phosphate (18,34). Cowser and Morton (44) reported good strontium removals using the softening process in a waste treatment plant. In a modified process, Goodgal _et_ _al_. (45) removed 99 per cent of the Sr from water initially containing 41 ppm strontium nitrate by aeration at pH 12.2. Strontium carbonate was precipitated by carbon dioxide in the air. Removals of 95 per cent of Y^{90}, 99 per cent of P^{32}, and 94 per cent of mixed fission products by lime-soda softening have been reported (18,34,46).

Removal of strontium in lime-soda ash softening was shown to be due to formation of mixed crystals of strontianite and calcium carbonate (46). Conditions promoting the removal of radiostrontium include the use of excess soda ash (23,43,46), high pH (43,46) high temperature (46), excess lime with an equivalent amount of soda ash (43), and recirculation of preformed solids (46). Burbank _et_ _al_. (36) found that up to 10 ppm added turbidity aided in lime-soda ash softening by providing nuclei for crystal formation and preventing the formation of poorly settling microcrystals.

Good strontium removals are a function of high softening efficiency. Where water was not completely softened, Downing _et_ _al_. (23) found a linear relationship between hardness removed and activity removed. Alexander _et_ _al_. (47) in testing water samples from 50 cities throughout the United States found that municipal softening plants removed up to 75 per cent of the stable strontium.

In summary, the lime-soda ash softening process appears to be the best general method of decontamination. It should be supplemented with clay and activated carbon for adsorption of hard-to-remove radionuclides. Coagulants and coagulant aids may be used to promote settling and improve clarification.

III. POLYELECTROLYTES

Polyelectrolytes, widely used as coagulant aids, are high molecular weight polymers possessing such characteristics of simple electrolytes as electrical charges or ionizable groups. They may be naturally occurring products such as gelatin, starch, or vegetable gums or may be synthetic materials such as polyacrylamides or copolymers of vinyl acetate and maleic anhydride. Cohen et al. (48) list three classes of polyelectrolytes according to the charge on the polymer: (a) negatively charged or anionic; (b) positively charged or cationic; and (c) compounds having both positive and negative charges called polyampholytes. To this list should be added a fourth, namely nonionic materials such as starch or guar gum. These materials are used in water treatment either alone or in conjunction with metal coagulants to improve clarification, to reduce the coagulant dosage required, to permit overloading of existing facilities, or to improve floc strength and filterability with consequent increase in filter runs.

The polymer molecules, which may be of colloidal dimensions, are surrounded by counterions of charge opposite that of the polymer molecules. This results in an uneven distribution of charges in solution such as in the clay-water system. Katchalsky (49) found that the activity of counterions in a polyelectrolyte solution decreased with increasing ionization of the polyelectrolyte because of their increased attraction to the polymer. The attraction of such charged polymers for ions increased rapidly with increasing valence of the ions. The polyelectrolytes could thus hold radioactive ions.

Fuoss and Sadek (50) demonstrated the strong electrical interactions of polyelectrolytes by mixing dilute solutions of cationic and anionic polymers. Mutual precipitation occurred in concentrations as low as 10^{-8} molar in polyelectrolytes.

Clay particles in water have been shown to bear a negative charge throughout the normal pH range used in water treatment (51). The addition of alum, however, will reduce or reverse this change over much of the pH range. Cationic polymers could adsorb on negative clay particles because of electrostatic attraction while electrostatic repulsion should play a part where anionic polymers were used. Where enough alum or other metal coagulant to reverse the charge was present, then these electrostatic forces would be reversed. Cohen _et al_. (48), using water of low turbidity, found the anionic polyelectrolytes to be effective only as aids to the metal coagulants. This electrical force picture does not, however, explain why the anionic aids alone will cause large flocs to form in slurry concentrations of clay.

Michaels and Morelos (52) listed three possible mechanisms for coagulation of clay with polyanions: (a) replacement of anionic groups of the clay with anionic groups of the polymer; (b) hydrogen bonding between the solid and the polymer; and (c) the formation of electrostatic bridges between the clay and the polymer by polyvalent cations. Working with slurry concentrations of clay, they concluded that hydrogen bonding between unionized carboxyl or amide groups on the polymer chain and oxygen atoms on the clay surface was responsible for the adsorption of polyanions.

Ruehrwein and Ward (53) treated montmorillonite with solutions of polycations or polyanions and then subjected the clay to X-ray analysis. The interplanar spacing increased with the polycation, indicating adsorption on the faces of the layers, but remained the same for the polyanion. This procedure, however, did not eliminate the possibility of anion adsorption on the edges of the layers where anion exchange sites are known to occur. Kaolinite was found to adsorb a polyanion with the amount adsorbed being proportional to the polymer concentration up to a saturation value approximately equivalent to the cation exchange capacity of the clay. Added NaCl diminished the repulsive forces between the polymer molecules so that they could be more closely packed on the particle surfaces and adsorption therefore increased.

As in Cohen's work, Ruehrwein and Ward observed that polycations were effective coagulants alone while polyanions served as coagulant aids after a flocculating dose of a metal coagulant had been added. To explain their results, they postulated the formation of polymer bridges between particles. These bridges should form better when the particles are already flocculated, otherwise many of the polyelectrolyte molecules would adsorb completely on individual particles. The polymers also bond particles in the process of flocculation, thus reducing their dispersion by Brownian motion.

In neutral polymolecules, Brownian movement alone determines the molecular shape to be a random coil as the molecular segments rotate around the chemical bonds. In charged polyelectrolytes, the shape results from the equilibrium between Brownian coiling tendency and repulsion between the charged sites along the polymer chain. Fuoss (54) measured the changes in viscosity of a polyelectrolyte as it was diluted and found that the more dilute solutions had much higher viscosities than would be extrapolated from the concentrated solutions. This was attributed to a stretching out of the polymer chains from mutual repulsion of the charged sites. Katchalsky (49) similarly found that specific viscosities of polyelectrolyte solutions increased with the degree of ionization of the polyelectrolyte up to about 60 per cent, then leveled off. This was also said to be due to stretching of the molecules as the electrostatic field strength increased. The rates of change of viscosity showed that at very low ionization, the molecular chains were so tightly coiled as to be almost spherical. At between approximately 10-20 per cent ionization, the molecules behaved as random flexing coils while at a high degree of ionization, they were fully extended and resembled rigid rods.

Michaels (55) performed controlled hydrolysis experiments on polyanions and concluded that there should be enough charged sites to extend the polymer chains sufficiently to permit interparticle bridging without increasing the charge density enough to interfere with adsorption on the negative clay particles. Partial charge neutralization by a metal coagulant should increase polyanion adsorption by reducing the repulsive forces. The pH of the solution would be expected to affect the ionization of the polymer and thus affect the adsorption and coagulation. Black (56) summarized some of the mechanical aspects of coagulation with polyelectrolytes.

Black and Hannah (51) studied the effects of eight coagulant aids on the charge of clay particles treated with varying dosages of alum. Using electrophoretic techniques, the particle charges were found to vary with changing dosages of alum and aid but the degree of clarification obtained could not be correlated with the final particle charge. The anionic polyelectrolytes would serve as aids to the metallic coagulants while the cationic polyelectrolytes would serve as sole coagulants. All of the polyelectrolytes could be made to either aid or inhibit coagulation by selection of dosages of alum or polyelectrolyte.

Black and Willems (57) found coagulant aids to be of value in removing color from soft waters. The lowest residual color was usually obtained where the combination of coagulant and aid neutralized the particle charge. However, the low pH used in color removal makes this process impractical for the removal of most radioisotopes from water.

Black and Christman (58) found both anionic and cationic aids to be of value in removing turbidity resulting from lime-soda ash softening. The charge of softening sludge particles was shown to be a function of the amount of Mg^{++} present in the water. Pure calcium carbonate was quite negative while pure magnesium hydroxide was slightly positive. Increasing amounts of Mg^{++} in a mixed sludge resulted in particle charges more positive than magnesium hydroxide. Two anionic aids improved clarification of suspensions containing negative particles while increasing the negative charge, therefore adsorption could not be simply electrostatic attraction.

On the practical side, Rice (59) listed three general methods by which coagulant aids work; they may increase the specific gravity of floc, the strength of floc, or the rate of coalescence of floc. They are particularly valuable in forming a rapidly settling floc in cold water where a metal coagulant alone is insufficient. Black et al. (60), using 17 different coagulant aids with alum to clarify clay suspensions, showed results ranging from great improvement in coagulation to complete inhibition of coagulation. Wadsworth and Cutler (61) coprecipitated anionic and cationic polyelectrolytes on kaolinite and hematite ore pulp to increase the settling rates.

Tests by Cohen et al. (48) showed the effectiveness of one anionic aid to be nearly independent of pH, alkalinity, hardness, and turbidity. However, the optimum dosage of anionic aid increased linearly with the alum dosage. The pH range of alum flocculation was not extended by the anionic aid. A cationic aid was effective only in moderately mineralized water and allowed alum coagulation in the presence of such interferences as sodium tripolyphosphate and lignins. Algae, which are negatively charged, were also removed from water by the cationic aid. This is potentially valuable in reducing contamination from organisms which are known to concentrate radioactive constituents. The nonionic aid tested was less effective than either the cationic or anionic aids.

Cowser et al. (62) studied the effects of eight coagulant aids on Oak Ridge National Laboratory radioactive waste effluent containing approximately 50 per cent of the activity associated with suspended solids. The most effective single aids for turbidity reduction, as determined by jar tests, were Hagan 50, Separan 2610, and Aerofloc 3000. Combinations of these aids with Hagan 18 gave further improvement. Plant trials showed that the combination of Hagan 50 and Hagan 18 would significantly reduce the effluent turbidity, giving a better floc even at low temperature, although complexing agents, such as cleansers and decontaminating compounds, sometimes seriously interfered with coagulation.

Newell and Christenson (30) found activated silica to be an aid to chemical flocculation of plutonium wastes where complexing agents such as citrates and phosphates were present. Hoyt (43) used sodium silicate to improve clarification with lime-soda softening and saw removals of Sr^{90}-Y^{90} activity increase from 76 per cent without the aid to 79 per cent with the aid. Activated silica with alum gave no significant removals of Sr^{89} or I^{131} in coagulation tests (23,32).

Rice (63) listed possible disadvantages of using the organic polyelectrolytes as a frequent shortening of filter runs with a resulting increase in backwash water requirements and the formation of a nonfilterable residual haze from colloidal aluminum oxide sol not already attached to the turbidity particles when the aid is added.

Johnson (64) photographically showed the effects of selected polyelectrolytes on floc formation in different types of water.

From a study of the behavior of many polyelectrolytes, certain procedures for their application become evident.

1. The aid must be applied in such a state that it may be rapidly dispersed throughout the water. Mixing must be fast and complete to ensure that all particles of turbidity come in contact with the polymer.
2. The order and time of addition of the coagulant and the aid must be evaluated. It generally seems better to add the aid shortly after the coagulant, although the reverse has been reported, particularly in softening with activated silica.
3. The dosages must be properly selected. An excess of aid may saturate all adsorption sites with single polymer molecules and interparticle bridging will be prevented. The adsorbed polyelectrolytes will then repel each other and stabilize the

suspension. The use of an aid will sometimes permit a substantial reduction in the amount of coagulant required for satisfactory clarification.

4. The effectiveness of an aid must be evaluated for a particular water depending on its chemical and physical properties and on the particular treatment process employed. The many interacting variables which affect coagulation also affect the choice of aid.

IV. EXPERIMENTAL MATERIALS AND PROCEDURES

The basic experimental procedures for water decontamination included coagulation with alum and ferric sulfate, softening with lime and soda ash, sorption on clays and activated carbon, carrier precipitation, and combinations of these treatments. Several coagulant aids of different types were used in conjunction with the basic treatments in an effort to increase the amount of radioactivity removed from water.

Materials

Alum

Alum used as coagulant was reagent grade aluminum sulfate represented by the formula $Al_2(SO_4)_3 \cdot 18\ H_2O$.

Ferric Sulfate

Ferric sulfate was reagent grade powder analyzing 75.1 per cent $Fe_2(SO_4)_3$. Dosages of ferric sulfate are reported as anhydrous $Fe_2(SO_4)_3$.

Lime

The lime used was reagent grade calcium hydroxide analyzing 98.0 per cent $Ca(OH)_2$.

Soda Ash

The soda ash was reagent grade sodium carbonate monohydrate. Dosages of soda ash are reported as anhydrous Na_2CO_3.

Clays

1. Kaolinite. The kaolinite used was EPK-Edgar Plastic Kaolin supplied by Edgar Plastic Kaolin Company, Edgar, Florida. A

data sheet is available with the chemical analysis and properties (65).

2. Fullers earth. The fullers earth was regular Florex XXX supplied by Floridin Company, Tallahassee, Florida. Definitive data are listed in Floridin's general catalog (66).

3. Illite. The illite was grundite from Illinois Clay Products Company, Joliet, Illinois. It was reported to contain 65-75 per cent illite.

4. Volclay. KWK Volclay was from American Colloid Company, Skokie, Illinois. It is a selected bentonite consisting of 90 per cent montmorillonite.

Coagulant Aids

1. Purifloc N17. Purifloc N17 (Separan NP 10) is a product of Dow Chemical Company, Midland, Michigan. It is described as an acrylamide type high molecular weight synthetic polymer having active groups which are adsorbed onto solids in suspension, bonding them together and drawing them into compact flocs (67). The mechanism is said to be nonionic and irreversible.

2. DIS-106. This aid is also a product of Dow Chemical Company and was particularly recommended for flocculation of solids in softening processes. It has not been approved for use in the treatment of potable water.

3. Nalcolyte 110. Nalcolyte 110 is a product of Nalco Chemical Company, Chicago, Illinois. It is described as a high molecular weight complementary coagulant (68).

4. Kelgin W. Kelgin W is a product of Kelco Company, New York, N. Y. This aid is a polymer of the sodium salt of mannuronic acid.

5. CMC 12H. CMC 12H is a product of Hercules Powder Company, Wilmington, Delaware. It is composed of sodium carboxymethylcellulose.

6. Ceron CN. Ceron CN is also a product of Hercules Powder Company. It is described as a natural polymer derivative and was found to be cationic (51). It is not approved for treatment of potable water.

7. Jaguar WPB. Jaguar WPB is a product of Stein, Hall and Company, Inc., New York, N. Y. Jaguar is a guar gum derived from the guar seed and is described as a polysaccharide consisting of a complex carbohydrate polymer of galactose and mannose. It is said to alter the electrokinetic properties of colloidal suspensions by a hydrogen bonding effect (69).

8. Permutit 65. Permutit 65 is a product of the Permutit Company, New York, N. Y. It is described as a complex organic compound having both cationic and anionic properties (70). It acts by being adsorbed on the floc particles. Distribution of this coagulant aid was discontinued after completion of the experimental work.

9. Activated Silica. The activated silica was prepared from N Brand sodium silicate supplied by Philadelphia Quartz Company, Philadelphia, Pa., by treatment with ammonium sulfate (71).

10. Burtonite #78. Burtonite #78 is a product of the Burtonite Company, Nutley, N. J. It is a refined guar gum and has served as a flocculant, filter aid, and flotation reagent for a variety of materials.

11. Drewfloc. Drewfloc is described as an alkaline alumina solution containing an organic "promoter" or coagulation aid plus a small amount of excess caustic for stabilization. It is made by E. F. Drew & Company, Inc., New York, N. Y.

Activated Carbon

1. Aqua Nuchar "A". Industrial Chemical Sales Division, West Virginia Pulp and Paper Company, New York, N. Y.

2. Nuchar C-190-N. Industrial Chemical Sales Division, West Virginia Pulp and Paper Company, New York, N. Y.

3. Hardwood Retort Carbon. Forest Products Chemical Company, Memphis, Tenn.

4. Norit C. American Norit Company, Inc., Jacksonville, Fla.

Chlorine

A high-test calcium hypochlorite containing a minimum of 70 per cent available chlorine was used in the removal of I^{131}.

Radioisotopes

The uranium was reagent grade uranyl nitrate hexahydrate. The other radioisotopes, as listed in Table 1, were obtained from Oak Ridge National Laboratory as carrier-free elements in acid or basic solutions.

Water

Most of the coagulation studies were made on Gainesville tap water with 5 ppm of added clay turbidity. Studies to evaluate the effect of lime-soda softening were made on a hard water from wells located near the laboratory. Analyses of the two waters performed by standard methods (72) are given in Table 2. Dosages of hydrated lime and soda ash were usually the stoichometric quantities required for complete softening and were, therefore, somewhat higher than the dosages which would be used in actual practice. However, undersoftening with lower dosages was sometimes used to detect the effects of lower pH.

TABLE 2

CHEMICAL ANALYSES OF WATERS

Constituent	Parts per Million Gainesville Tap Water	Parts per Million Well Water
Total dissolved solids	147	391
Iron, Fe	0	0
Calcium, Ca	13	108
Magnesium, Mg	11	2.4
Sodium and potassium, Na+K as Na	4.3	1.1
Carbonate ion, CO_3	17	0
Bicarbonate ion, HCO_3	15	298
Sulfate ion, SO_4	18	8.7
Chloride ion, Cl	20	21
Carbonate hardness as $CaCO_3$	40	244
Non-carbonate hardness as $CaCO_3$	38	36
Total hardness as $CaCO_3$	78	280
pH	9.24	7.46

Procedures

Waters for activity removal studies were drawn into large polyethylene containers and thoroughly mixed with the selected radioisotope. With the exception of uranium, initial count rates were generally in the range 500 to 3000 cpm/ml. Where tap water was used, 5 ppm of finely ground kaolinite was added to the water to provide nuclei for floc formation. After further mixing, 600 ml samples were pipetted into 1-liter pyrex beakers which were then placed on the jar test machines.* Twelve samples could be run at one time on the two units.

The paddle speed was set at 100 rpm and 1.00 ml samples were withdrawn from four beakers and placed in aluminum planchets for counting initial activity. Measured amounts of adsorbents, coagulants, and coagulant aids were then added to the beakers and stirring was continued at 100 rpm.

All of the coagulant aids, with the exception of activated silica and Drewfloc, were obtained as solids. These were dissolved or suspended in distilled water before use by stirring with a magnetic mixer. The coagulants and softening reagents were also made up as water solutions or suspensions. The carbons and clays were added as dry solids.

Where an adsorbent was used or where the coagulant was added before the aid, two minutes mixing was allowed between increments to permit the adsorbent to wet or to give a floc time to form. Three minutes after the last reagent was added, the speed was reduced to

---

*Laboratory stirrer made by Phipps and Bird, Richmond, Va.

30 rpm and stirring was continued for 30 minutes permitting the floc to grow and incorporate the solids in the water. At the end of the slow mixing period, the machines were stopped and the paddles were removed from the beakers.

After a one-hour settling period, 1.00 ml samples were withdrawn from just below the water surfaces in the beakers and placed in planchets for counting the remaining unsettled activity. Fifty ml samples were poured from each beaker at this time if final turbidities were to be measured. Ten ml samples were withdrawn and centrifuged at approximately 3200 rpm (10,000 fpm) for 15 minutes to remove suspended material; 1.00 ml samples of the supernatant were then taken for counting as an estimate of additional activity which might be removed by filtration. Hoyt (43) found that centrifugation and filtration gave comparable removals of activity.

The samples were dried under heat lamps and counted on Baird Atomic equipment, including a Model A-227 gas-flow proportional counter, Model 132 Scaler, and Model 750 automatic sample changer. Samples were timed for 900 or 3000 counts several times and results were averaged. Counting efficiency, as determined from a radium D and E standard previously calibrated by the National Bureau of Standards, was approximately 43 per cent. Because of the wide differences in types and energies of emissions, no effort was made to calculate counting efficiencies of individual isotopes and activities are expressed in cpm/ml. The counter was operated in the Geiger region at 2200 volts.

The measured counts were corrected for background and volume change on addition of reagents and the percentage activity removed was calculated as follows: Per cent activity removed =

$$\frac{\left[(\text{cpm/ml})_i-(\text{cpm})_b\right]-\left[(\text{cpm/ml})_f-(\text{cpm})_b\right]\left[\frac{600 + A}{600}\right]}{(\text{cpm/ml})_i-(\text{cpm})_b} \text{ X } 100$$

where i = initial activity (average of 4 samples)
f = final activity
b = background count
A = total volume in ml of aids and coagulants added to the beaker sampled.

The per cent transmittance of turbidity samples was measured on a photoelectric colorimeter* using a red filter and 7.5 cm light path. Transmittance values were converted to A.P.H.A. turbidity units by means of a curve prepared with fullers earth standards measured on both the colorimeter and the Jackson Candle Turbidimeter. The pH of the remaining solution was measured on a Beckman Zeromatic pH Meter.

The preceding methods were generally followed for all isotopes. Special modifications and procedures are described in the discussions of individual isotopes.

---

*Lumetron Model 450, made by Photovolt Corp., New York, N. Y.

V. DISCUSSION OF RESULTS

The data are divided into five groups corresponding to the five radioisotopes studied. Common abbreviations used in the tables and figures are listed in the Appendix. Solid lines in the figures represent settled samples while broken lines show activities remaining in centrifuged samples. Values in parentheses in the tables are turbidities of the supernatant in settled samples.

In evaluating the significance of activity removals, the amount by which the initial activities exceed the maximum permissible concentrations (MPC) for water must be considered. Where initial activities are high in relation to MPC and efficiencies of decontamination processes are low, a given increase in per cent activity removed by a polyelectrolyte may not be nearly so significant as the same increase in per cent activity removed with a high efficiency process. If, for example, 99.9 per cent of the initial activity must be removed to reach the MPC and two processes removed 99.0 per cent and 50.0 per cent of the activity respectively, an increase in removal of 0.9 per cent for both processes would be much more significant for the first process. In the one case, activities would be reduced from (10 x MPC) to the MPC value while in the other the change would be from (500 x MPC) to (491 x MPC). Percentage removals much greater than 99.9 per cent are often required in practice to reduce activities of liquid wastes to permissible levels.

Removal of Cs^{137}-Ba^{137m}

Cesium is one of the alkali metals located in Group I of the periodic system. These elements are extremely reactive and form mostly soluble compounds.

Cs^{137}, with a half life of 30 ± 3 years (73), decays by β emission to Ba^{137m}, which has a half life of 2.6 minutes and emits γ radiation. Because of the different half lives, cesium would be the predominate active species present in an equilibrium mixture of the two radioisotopes.

Coagulation of tap water containing Cs^{137} with variable dosages of alum and ferric sulfate removed only 0-10 per cent of the initial activity. The hydrous oxide flocs are not good adsorbers for cesium. On the other hand the clays are quite effective for sorption of Cs^{137} from solution as shown in Figure 1 and Table 3. Illite and fullers earth both exhibited peak centrifuged removals of activity greater than 92 per cent at 1000 ppm dosages. The decreased pH (6.8) with 5000 ppm illite probably contributes to the lower activity removals with this dosage of clay. Reproducibility of results is shown by the duplicate illite runs. Where pH was varied with 0.5 N NaOH or H_2SO_4, centrifuged removals of activity generally increased with increasing pH but kaolinite and illite exhibited sharp drops in settled removals near pH 7 as shown in Figure 2 and Table 4.

The polyelectrolytes differed in their action on coagulation and activity removal with clays. Figure 3 shows that Purifloc N17, which normally coagulates slurry concentrations of clay, reduced final turbidities and consequently increased settled activity removals with 1000 ppm fullers earth or illite. Centrifuged removals, however, decreased slightly with all dosages of this aid. Activated silica interfered with coagulation of clay where an alum dosage of 17 ppm was optimum for turbidity reduction without any coagulant aid. Residual activities also increased with increasing dosages of activated silica. The alum with 1000 ppm fullers earth removed nearly 95 per cent of the activity. A dosage of 10 ppm ferric sulfate with clay gave activity removals comparable to alum. Nalcolyte 110, Kelgin W, and Jaguar WPB had little effect on activity removals with 1000 ppm fullers earth or illite and 10 ppm ferric sulfate. Nalcolyte 110 and Jaguar WPB significantly reduced the turbidities while Kelgin W showed little improvement in coagulation under the test conditions.

Softening of well water with lime and soda ash did not remove Cs^{137}. However, clays used in conjunction with lime-soda ash softening will remove almost 98 per cent of the activity. Table 5 shows steadily increasing activity removals with increasing dosages of lime. DIS-106, Ceron CN, and activated silica all reduced turbidity with lime, soda ash, and illite or fullers earth. Figures 4, 5, and 6 show removals of activity by settling generally increasing with decreasing final turbidity, but centrifuged removals have a slight downward trend with increasing dosages of these aids.

An anionic aid, Purifloc N17, had little effect on either activity removal or turbidity when added after 1 ppm Ceron CN, a cationic aid. Ceron CN was of no value for increasing uptake of Cs^{137} by Volclay with lime and soda ash. It did increase activity removals by settling mixed illite and fullers earth, lime, and soda ash, and did reduce the final turbidity. Figure 7, however, shows centrifuged activity removals to be nearly constant. Variations in the initial activity from 567 cpm/ml to 10,000 cpm/ml caused little change in percentage of activity removed by settling and centrifuging mixed illite and fullers earth, lime, soda ash, and 0.5 ppm Ceron CN.

Magnesium, added as $MgCl_2$, increased settled activity removals but slightly decreased centrifuged removals with mixed illite and fullers earth, lime, and soda ash as shown in Figure 8. The final turbidity was reduced to 0 with 33 ppm added Mg; better clarification than with any of the polyelectrolytes. Lime and soda ash dosages were the stoichometric quantities required for complete softening including removal of the added magnesium.

Figure 9 shows that traces of stable cesium greatly inhibit removal of Cs^{137} from water by clays. Apparently the clays have a relatively low affinity for cesium or there are few lattice sites available for adsorption and exchange of this element.

An activated carbon, Norit C, with lime and soda ash, removed only 37 per cent of the activity in dosages up to 5000 ppm.

In summary, neither coagulation nor lime-soda softening alone will remove Cs^{137}-Ba^{137m} from water. Two clays, illite and fullers earth, are effective adsorbents for cesium but large dosages (1000 ppm) are required for good removal. For best results the pH should be held above pH 9.

The polyelectrolytes reduced suspended activity by aiding in clarification of clay slurries after softening but slightly reduced centrifuged activity removals. Minimum dosages of the coagulant aids which give satisfactory settling should be used to prevent interference with activity uptake since the rapid formation of large flocs by higher dosages of aid decreases the surface area available for adsorption. Still higher concentrations of polyelectrolytes may coat the particles and prevent both adsorption and coagulation.

Removal of Sr^{89}

Strontium is an alkaline earth metal located in Group II of the periodic system. These elements are somewhat less reactive than the alkali metals and generally form less soluble compounds.

Sr^{89} has a half life of 53 days (73) and decays by β emission. It may be readily precipitated as the carbonate or phosphate but an extremely high percentage removal is difficult to obtain.

Extensive coagulation tests using alum or ferric sulfate with variable dosages of seven polyelectrolytes failed to remove more than 30 per cent of the initial activity. Softening tests, using the lime dosage calculated for complete softening, gave steadily increasing activity removals with increasing dosages of soda ash as shown in Figure 10.

Table 6 shows that low dosages of DIS-106 slightly increased both settled and centrifuged activity removals with theoretical dosages of lime and soda ash. DIS-106, however, decreased activity removals with 100 per cent excess lime and soda ash equivalent to non-carbonate hardness plus excess lime. Theoretical lime dosages with both theoretical (35 ppm) and excess (200 ppm) soda ash dosages were not significantly improved in removal of Sr^{89} when used with Kelgin W, Nalcolyte 110, Jaguar WPB, Permutit 65, activated silica, CMC 12H, and

Purifloc N17. Large dosages of aid almost always inhibited activity removal.

Figure 11 compares the effectiveness of the different clays in removing Sr^{89} from water. Volclay was better than the other clays but 5000 ppm Volclay removed only 66 per cent of the activity upon centrifuging. Purifloc N17, Kelgin W, Jaguar WPB, CMC 12H, and Nalcolyte 110 all gave good clarification when used with 5000 ppm Volclay as shown in Table 7. Permutit 65 was less effective as a coagulant while activated silica alone caused very high final turbidities. Some settled activities increased while others decreased with decreasing final turbidity. Centrifuged activities showed little tendency to change. Activity removals with kaolinite, fullers earth, and illite were not raised to practical levels by the coagulant aids. The effectiveness of any given polyelectrolyte was dependent on the type of clay and also on the order in which the aid and the clay were added to the contaminated water.

All four clays were found to be of some value as adsorbents for Sr^{89} with lime-soda softening although Volclay was the only one which removed more than 93 per cent of the activity. Removals of activity increased slightly when the settled softening sludge and clay were mixed with 5 ppm Purifloc N17 and then resettled and sampled as shown in Table 8.

Tables 9-11 show that DIS-106, Purifloc N17, and Kelgin W slightly increased settled removals with lime, soda ash, and 5000 ppm Volclay. Final turbidities were quite high. Up to 99.5 per cent of the activity was removed by centrifuging samples containing 165 ppm soda ash in excess of calculated requirements.

Since the well water used for softening studies contained so little magnesium, this element was added as $MgCl_2$ in special tests to determine its effect on removal of Sr^{89}. With lime and soda ash dosages equivalent to the water hardness plus the extra magnesium, activity removal was depressed slightly. Added magnesium increased settled activity removals and decreased final turbidities where 5000 ppm Volclay was used with the same lime and soda ash dosages. All samples thus treated contained 5 ppm DIS-106.

Low dosages of stable strontium had little effect on activity removal when used with theoretical lime and soda ash dosages and 5 ppm DIS-106. Variable dosages of Purifloc N17 with theoretical lime dosages, excess soda ash, Volclay, and 10 ppm stable strontium raised settled activity removals from 93.5 per cent to 99.2 per cent with little change in centrifuged activity removals as shown in Table 12. Final turbidity was reduced from 1200 to 15 with 15 ppm N17. With excess lime, equivalent soda ash, Volclay, and 10 ppm stable strontium, 5 ppm Purifloc N17 reduced turbidity from 325 to 11 but had little effect on activity removal as shown in Table 13.

In summary, neither coagulation nor softening alone were effective for removal of Sr^{89} from water. None of the polyelectrolytes significantly decreased the final activities with these processes alone.

High dosages of Volclay with theoretical lime dosages and excess soda ash gave the only activity removals greater than 99 per cent. The polyelectrolytes were of value here for reducing the turbidity and associated activity but centrifuged activity removals frequently decreased with decreasing final turbidity. The dosage of aid must reflect a balance between formation of floc large enough to settle but still small enough to have a large area for adsorption. There is a conflict in polyelectrolyte requirements between the porous clays, which may take up relatively large amounts of aid, and the crystalline sludge particles which need very little. Fractionation of the solids may thus occur upon coagulation leaving fine turbidity in suspension.

Removal of Pm^{147}

Promethium is one of the rare-earth or lanthanide elements. Their characteristics and most stable oxidation state is +3. The ions have a strong affinity for cation exchange materials and this property is used in their separation.

Pm^{147} has a half life of 2.6 years (73) and decays by β emission. Promethium has not been found in nature but is a product of uranium fission.

Unlike cesium and strontium, promethium is effectively removed from water by coagulation. Figure 12 shows ferric sulfate to be more effective than alum, removing 99.1 per cent of the activity in a dosage of 40 ppm. Settled and centrifuged activity removals without any coagulant were 36 per cent and 77 per cent respectively, indicating that the activity was either in a precipitated state or was associated with the 5 ppm kaolinite in the tap water.

Sulfuric acid and sodium hydroxide (0.5N) were used with the optimum alum and ferric sulfate dosages to determine the pH of best activity reduction. As shown in Figure 13, removals were highest near pH 7 but were relatively constant above this value.

Table 14 shows the effects of seven coagulant aids on removal of Pm^{147} with 60 ppm alum or 36 ppm ferric sulfate. With alum, low dosages of Nalcolyte 110, Kelgin W, and Permutit 65 gave small increases in centrifuged activity removals. Settled removals were somewhat erratic and did not necessarily parallel centrifuged removals. CMC 12H and activated silica decreased centrifuged removals but increased settled removals. With ferric sulfate, Purifloc N17 and CMC 12H increased centrifuged activity removals slightly. Dosages of some coagulant aids for good coagulation were quite critical and floc size was not a good indication of activity removal to be expected. The order in which the aid and coagulant were added was also a factor in decontamination.

Table 15 shows all clays to be very effective in adsorbing Pm^{147} from water. Figure 14 shows activity removed by centrifuging clay dosed waters. Purifloc N17, Kelgin W, and activated silica slightly reduced activity removals when used with 500 ppm clay and ferric sulfate or alum. Purifloc N17 and Jaguar WPB both increased floc size with clay but activity removals were greatly reduced. Settled activity removals with fullers earth and ferric sulfate remained essentially constant and centrifuged removals increased from 99.7 per cent to 99.8 per cent as initial activities were increased from 3100 cpm/ml to 33,000 cpm/ml.

In softening tests with variable amounts of lime and soda ash, as shown in Table 16, theoretical dosages of both reagents gave the best settled activity removal (95.4 per cent) while the theoretical lime dosage with excess soda ash gave the best centrifuged removal (99.7 per cent). Figure 15 shows removal of Pm^{147} from well water with 46 ppm soda ash and variable dosages of lime.

Nine coagulant aids were used in softening the hard well water with theoretical dosages of lime and soda ash as shown in Table 17. Activated silica, shown in Figure 16, was the only aid which satisfactorily reduced the turbidity and increased settled activity removals. Daily variations were noted in turbidities and settled removals where aids were not used but centrifuged removals all exceeded 97 per cent.

Table 18 shows that increasing dosages of Purifloc N17 and Jaguar WPB produced minimums in turbidities with lime, soda ash, and clay but steadily reduced activity removals. Where two different types of solid surface exist, one is likely to become saturated with polyelectrolyte before the other. Increasing dosages of coagulant aid may then be dispersing one solid while it is coagulating the other.

Figure 17 shows the reduction of activity in solution by Hardwood Retort Carbon. This material was not as effective as an equal weight of clay. Purifloc N17 flocculated carbon but did not predictably affect activities, while increasing dosages of Kelgin W caused activity removals to decrease with 250 ppm fullers earth and 250 ppm carbon.

In summary, coagulation with alum and ferric sulfate or softening with theoretical dosages of lime and soda ash remove 95-99 per cent of Pm^{147} activity. Clay is useful for making high removals consistent and extends the range as high as 99.7 per cent. Although small dosages of some polyelectrolytes may decrease residual activity, accurate control of decontamination would be difficult since neither floc size nor final turbidity is indicative of activity removed. Activated silica was useful with lime and soda ash alone for both decontamination and turbidity reduction.

Removal of I^{131}

Iodine is one of the halogens and is located in Group VII of the Periodic System. Iodide ion is easily oxidized to the free element by chlorine or hypochlorite and may be further oxidized to the iodate or periodate in alkaline solution. Most of the iodides are quite soluble in water.

I^{131} with a half life of 8.08 days (73) decays by both β and γ emission with a wide range of energies. Because of the volatility of iodine at high temperature, it was necessary to dry all planchets with this isotope in air without the application of heat.

Coagulation with alum and ferric sulfate generally removed less than 10 per cent of the I^{131} present. Aqua Nuchar A and C-190-N removed up to 59 per cent of I^{131} but dosages as high as 5000 ppm were required as shown in Figure 18.

Figure 19 shows the improvement in activity removal by use of small dosages of chlorine (0.05 - 0.10 ppm) with alum and ferric sulfate. The chlorine dosage for optimum removal was quite critical and the maximum efficiency was still only about 30 per cent. Similar results were obtained using chlorine with lime and soda ash or with 100 ppm fullers earth.

Figure 20 shows the effect of small dosages of chlorine on removal of I^{131} with C-190-N. Over 80 per cent activity was removed by centrifuging with a chlorine dosage of 0.1 ppm. Figure 21 shows the effect of the order in which the chlorine and the activated carbon are added to the water to be treated. When the carbon is added first, the peak removals are not obtained. Raising the carbon dosage from 100 ppm to 1000 ppm did not increase the per cent activity removed as shown in Figure 22. Using a fixed chlorine dosage of 0.1 ppm, activity removal with Aqua Nuchar A began to level off at a carbon dosage of 50 ppm as shown in Figure 23.

Varying the pH between 6.8 and 10.2 with sulfuric acid or sodium hydroxide had little effect on activity removal with 0.1 ppm chlorine and 100 ppm Aqua Nuchar A. Alum and ferric sulfate generally aided in coagulation of carbon and increased settled removals but slightly decreased centrifuged removals as shown in Table 19. Activity removals with chlorine, carbon, lime, and soda ash, shown in Figure 24, were lower than those with chlorine and carbon alone or with chlorine, carbon, and coagulants.

Figure 25 shows that the per cent of I^{131} removed with chlorine and Aqua Nuchar A tended to increase with increasing activity. Stable iodide in dosages greater than 0.05 ppm inhibited removal of I^{131} with fixed dosages of chlorine and Aqua Nuchar A as shown in Figure 26.

Table 20 shows that the coagulant aids used with chlorine and Aqua Nuchar A inhibited settled activity removals but left centrifuged removals practically unchanged. Activated silica with alum was of value in removing the carbon and activity by settling but centrifuged removals decreased.

In summary, the only effective method found for removing I^{131} with materials generally available in water treatment plants involved chlorination followed by adsorption of liberated iodine on activated carbon. The optimum chlorine dosages were quite small and had to be selected by effects on activity removal alone since residuals were too small to be detected. Chlorine requirements should also depend on other oxidizable materials in the water.

Normal prechlorination could not be used with iodine removal because the residuals would generally exceed the critical dosages for activity removal. Gainesville tap water could not be used for removal tests because of its chlorine content.

Alum and ferric sulfate with low dosages of aids may be used to coagulate the carbon. Lime and soda ash or polyelectrolytes alone appear to inhibit removal of activity.

Although C-190-N gave slightly higher removals than Aqua Nuchar A, the latter was preferred since it flocculated better and did not float on the surface. The clays alone were very poor decontaminants.

Removal of Uranium

Uranium is one of the actinide elements and is widely distributed in the earth's crust. The primary isotope in natural uranium is U^{238} with small amount of U^{235} and U^{234}. Uranium initially decays by α and γ emission starting a long disintegration series which finally ends with stable lead. Radium which is included in this series is one of the most dangerous isotopes when ingested.

U^{238} has a half life of 4.51×10^9 years (74), therefore relatively large amounts are required to give high count rates unless the working solutions are concentrated. Uranium forms insoluble salts with the alkali and alkaline earth metals indicating that lime-soda softening would possibly be an effective method for its removal. Removal of uranium was studied at two activity levels; in concentrated solutions containing approximately three grams of uranyl nitrate hexahydrate per liter, and in dilute solutions containing approximately 30 mg of uranyl nitrate hexahydrate per liter. With the concentrated solutions, 1 ml samples were counted as with the other isotopes, while 50 ml settled samples only were concentrated and counted for the dilute solution.

The addition of both excess lime and caustic soda to a concentrated uranium solution reduced the count rate to background with 1.00 ml samples as shown in Figure 27. This is presumably due to precipitation of the insoluble uranates. For best results, the final pH should be greater than 11.0. The addition of sodium carbonate to a concentrated uranium solution caused a precipitate to form but this dissolved with excess soda ash because of complex formation.

Alum and ferric sulfate with reduced lime dosages increased activity removal by settling as shown in Tables 21 and 22. Volclay had no apparent effect on precipitation of uranium from concentrated solutions with lime.

In the dilute solutions, the normal alkalinity of the water precipitated much of the uranium. Alum and ferric sulfate coagulated the fine suspension and removed 70-75 per cent of the activity. A dosage of 500 ppm kaolinite increased activity removal with alum by about 5 per cent and gave more consistent results with ferric sulfate as shown in Figure 28. Figure 29 shows the effect of variable dosages of lime for precipitation of uranium from dilute solutions. Almost 88 per cent of the activity was removed with 500 ppm kaolinite and

250 ppm lime at pH 10.9.

None of the group of eight coagulant aids was of value for increasing activity removal with 30 ppm alum or with 500 ppm kaolinite and 30 ppm alum as shown in Table 23. No significant improvement was noted when the same coagulant aids were used with 25 ppm ferric sulfate or with 500 ppm kaolinite and 25 ppm ferric sulfate as shown in Table 24. Table 25 shows that the coagulant aids generally increased turbidity or decreased activity removal with lime and soda ash used alone or in conjunction with 500 ppm kaolinite. Exceptions were Kelgin W and activated silica, shown in Figures 30 and 31 respectively, both of which gave excellent turbidity reduction and some increase in activity removal.

In summary, uranium concentrations may be reduced well below the MPC by precipitation of the uranates with lime or caustic soda. In concentrated solutions, the uranium forms a heavy floc which settles readily.

In dilute solutions, alum and ferric sulfate were necessary to coagulate the uranium. The polyelectrolytes did not increase activity removal by coagulation but Kelgin W and activated silica aided in removal of activity with lime and soda ash.

VI. CONCLUSIONS

The effects of eleven polyelectrolyte coagulant aids on the removal of turbidity and activity are summarized in Tables 26 and 27 respectively. These tables are subdivided into groups corresponding to the basic removal processes employed and polyelectrolytes are rated on arbitrary scales designed to separate them according to their relative efficiencies in each process.

The coagulant aids are primarily of value in removing from water clay or other solids with which the activity might be associated. Improvements in removal of soluble activity with the aids are generally small and will not yield a safe drinking water with conventional water treatment processes unless initial activities are relatively low. The polyelectrolytes should give much greater benefits with actual fallout products which contain most of the activity in an insoluble form.

No coagulant aid was found which would be satisfactory for all removal processes. The type and dosage of coagulant or added turbidity are predominant factors in the selection of an aid. Dosages of many of the polyelectrolytes are quite critical and excessive amounts will generally interfere with coagulation rather than aid it. Their effectiveness varies with the different radioisotopes.

For removal of the soluble activity which depends on adsorption by a solid, the minimum dosage of a coagulant aid that forms a floc which will settle during the available retention time should be used. Higher dosages will decrease the surface area of the solid, and consequently, decrease the adsorption of activity. Some of the aids which give the best turbidity reduction thus increase the activity remaining in solution.

For removal of specific radioisotopes from water, the following basic procedures are recommended. Those polyelectrolytes rated "A" in the tables for the given process should be tried to see which is best under local conditions.

1. Cesium. Illite or fullers earth with lime and soda ash dosages equivalent to the water hardness are most effective for removal of cesium.

2. Strontium. Volclay with theoretical lime dosages for softening and excess soda ash are best for removal of strontium.

3. Promethium. Good removals of promethium are obtained with both alum and ferric sulfate coagulation and with lime-soda softening. Any of the clays are useful for broadening the range of dosages giving good coagulation, and also appear to adsorb some of the promethium.

4. Iodine. Small dosages of chlorine followed by adsorption of liberated iodine with activated carbon have proved to be useful for removal of I^{131} from water.

5. Uranium. Uranium is conveniently removed from water by precipitation with lime. Alum or ferric sulfate may be used to coagulate the suspension.

In an emergency situation, the best modified conventional process for water treatment would appear to be lime-soda softening in conjunction with clay treatment. Naturally occurring soft waters should be treated with enough lime to bring the pH within the range of 10-11 and enough soda ash to precipitate the added calcium. Polyelectrolytes may be used to reduce the turbidity. However, the clay and softening sludge should be allowed to contact the water as long as possible before the coagulant aid is added. Series operation of treatment units may be advantageous since the polymers should be thoroughly mixed with the water. Because of the many radioisotopes present in fallout and the different types of local clay which might be used, no specific polyelectrolyte can be recommended. The tables may be consulted to find those materials most likely to work in a given situation. In any case, jar tests should be used beforehand to determine the optimum dosage of polyelectrolyte needed to reach the minimum residual turbidity in the water.

APPENDICES

APPENDIX I

Abbreviations Used in Tables and Figures

I_o	Initial Activity (cpm/ml)
S	Activity Removed by Settling
C	Activity Removed by Centrifuging

Clays

K	Kaolinite
FE	Fullers Earth
V	Volclay
I	Illite

Coagulant Aids

106	DIS-106
N17	Purifloc N17
110	Nalcolyte 110
W	Kelgin W
12H	CMC 12H
CN	Ceron CN
WPB	Jaguar WPB
65	Permutit 65
"SiO_2"	Activated Silica
78	Burtonite #78
D	Drewfloc

APPENDIX II

TABLES

TABLE 3

SORPTION OF Cs^{137} FROM TAP WATER BY VARIABLE DOSAGES OF CLAY

Clay	I cpm/ml	pH	Per Cent Activity Removed by Settling					
			ppm Clay					
			0	50	200	500	1000	5000
K	2844	8.8-7.9	0	0	19.4	16.3	39.2	73.7
FE	3047	8.6-8.4	9.0	32.9	60.9	77.1	86.0	61.0
V	3047	8.6-9.2	7.9	15.6	19.5	28.9	36.8	65.9
I	2844	8.8-6.9	29.2	34.9	52.5	57.1	58.6	78.0
I	3047	8.6-6.8	21.2	27.2	51.9	57.9	63.4	81.5

TABLE 4

THE EFFECT OF pH ON SORPTION OF Cs^{137} FROM TAP WATER BY KAOLINITE AND VOLCLAY

Clay	pH	I_o cpm/ml	Per Cent Activity Removed	
			Settled	Centrifuged
5000 ppm Kaolinite	5.8	3416	83.4	85.9
	7.0	3416	81.7	86.5
	7.5	3416	79.1	85.6
	8.1	3416	83.0	86.1
	9.0	3416	83.5	87.8
	9.8	3416	88.6	91.3
5000 ppm Volclay	6.2	2957	52.2	78.4
	7.0	2957	56.1	81.5
	7.9	2957	62.0	82.1
	8.5	2957	60.8	84.5
	9.3	2957	66.6	85.0
	10.1	2957	69.0	85.6

TABLE 5

THE EFFECT OF VARIABLE DOSAGES OF LIME ON REMOVAL OF Cs^{137} FROM TAP WATER WITH 1000 ppm ILLITE AND 25 ppm FERRIC SULFATE

ppm Lime	pH	Settled Turbidity	Per Cent Activity Removed	
			Settled	Centrifuged
0	6.8	20	91.8	92.1
5	7.1	14	92.7	93.5
8.5	7.2	13	90.3	92.7
14	7.8	22	92.1	94.2
20	8.5	17	95.5	94.4
35	9.3	15	96.2	95.4
50	9.5	11	95.6	96.8
80	10.1	9	97.1	97.9

TABLE 6

REMOVAL OF Sr^{89} FROM WELL WATER WITH 188 ppm LIME, 35 ppm SODA ASH, AND DIS-106

ppm 106	I_o cpm/ml	pH	Per Cent Activity Removed	
			Settled	Centrifuged
0	653	10.1	77.3	83.0
0.1	653	10.1	81.2	84.1
0.3	653	10.2	81.7	84.3
0.5	653	10.2	78.9	82.3
1	653	10.2	81.0	81.7
5	653	10.1	79.8	82.1

TABLE 7

REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY AND VARIABLE DOSAGES OF COAGULANT AIDS

				Per Cent Activity Removed											
				ppm Aid											
				0			0.2			1			10		
Aid	Order of Addition	I cpm^{9}/ml	pH	S		C	S		C	S		C	S		C
N17	Aid + V	436	8.2	64.5	(69)	68.8	62.8	(46)	68.0	72.0	(12)	70.3	65.3	(7)	67.2
N17	V + Aid	436	8.2				71.3	(54)	67.5	68.8	(66)	66.0	63.2	(9)	63.2
W	Aid + V	310	8.2	65.9	(60)	67.6	69.8	(49)	69.8	73.8	(31)	69.8	67.3	(18)	73.1
W	V + Aid	310	8.2				73.6	(73)	75.2	75.7	(44)	73.4	75.0	(29)	75.7
WPB	Aid + V	1743	8.3	62.9	(54)	65.5	60.7	(42)	65.5	67.9	(39)	67.5	64.7	(4)	66.2
WPB	V + Aid	1743	8.3				67.7	(39)	67.0	57.8	(32)	62.7	67.2	(3)	65.9

TABLE 7 - CONTINUED

Aid	Order of Addition	I cpm^9/ml	pH	Per Cent Activity Removed							
				ppm Aid							
				0		0.2		1		10	
				S	C	S	C	S	C	S	C
12H	Aid + V	1679	8.3	66.6	64.6	67.2	61.0	63.5	67.9	69.0	61.2
				(64)		(24)		(4)		(50)	
12H	V + Aid	1679	8.3			63.0	70.1	64.4	67.8	62.5	63.0
						(28)		(3)		(26)	
65	Aid + V	1743	8.3	63.7	66.8	68.0	62.2	68.4	63.3	64.8	65.3
				(64)		(54)		(32)		(49)	
65	V + Aid	1743	8.3			67.6	64.3	66.0	65.1	67.7	65.7
						(39)		(37)		(39)	
				0		0.5		5		25	
110	Aid + V	1679	8.3	66.1	72.1	64.2	71.7	66.3	70.4	62.9	67.9
				(78)		(41)		(21)		(9)	
110	V + Aid	1679	8.3			66.4	67.0	63.2	64.7	66.7	62.2
						(23)		(11)		(3)	

TABLE 7 - CONTINUED

<table>
<tr><th rowspan="3">Aid</th><th rowspan="3">Order of Addition</th><th rowspan="3">I
cpm^{9}/ml</th><th rowspan="3">pH</th><th colspan="8">Per Cent Activity Removed</th></tr>
<tr><th colspan="8">ppm Aid</th></tr>
<tr><th colspan="2">0</th><th colspan="2">5</th><th colspan="2">25</th><th colspan="2">100</th></tr>
<tr><th></th><th></th><th></th><th></th><th>S</th><th>C</th><th>S</th><th>C</th><th>S</th><th>C</th><th>S</th><th>C</th></tr>
<tr><td>"SiO_2"</td><td>Aid + V</td><td>467</td><td>8.1-8.8</td><td>60.1</td><td>66.6</td><td>59.8</td><td>61.6</td><td>66.4</td><td>68.9</td><td>54.5</td><td>64.8</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2">(78)</td><td colspan="2">(145)</td><td colspan="2">(450)</td><td colspan="2">(1150)</td></tr>
<tr><td>"SiO_2"</td><td>V + Aid</td><td>467</td><td>8.1-8.8</td><td></td><td></td><td>69.1</td><td>72.0</td><td>65.1</td><td>72.2</td><td>63.8</td><td>65.3</td></tr>
<tr><td></td><td></td><td></td><td></td><td colspan="2"></td><td colspan="2">(300)</td><td colspan="2">(675)</td><td colspan="2">(1500)</td></tr>
</table>

TABLE 8

REMOVAL OF Sr^{89} FROM WELL WATER WITH LIME, SODA ASH, AND VARIABLE DOSAGES OF CLAYS

ppm Clay	ppm Lime	ppm Soda Ash	I_o cpm/ml	pH	Per Cent Activity Removed			
					No Aid		5 ppm N17*	
					S	C	S	C
			KAOLINITE					
0	188	35	1466	9.7	79.1	81.9	76.8	82.3
100	188	35	1466	9.7	81.9	80.5	79.3	82.2
500	188	35	1466	9.7	81.0	80.5	80.5	80.0
1000	188	35	1466	9.7	78.7	82.9	81.1	82.8
2500	188	35	1466	9.6	82.8	83.5	85.6	84.5
5000	188	35	1466	9.2	81.7	85.4	86.3	87.2
			FULLERS EARTH					
0	188	35	1466	9.8	81.3	83.8	78.4	83.0
100	188	35	1466	9.6	80.2	85.6	81.6	83.7
500	188	35	1466	9.6	85.1	86.6	84.0	85.7
1000	188	35	1466	9.5	85.4	85.9	86.2	85.2
2500	188	35	1466	9.2	88.3	89.3	89.6	89.7
5000	188	35	1466	8.8	91.6	92.5	91.8	92.4

TABLE 8 - CONTINUED

ppm Clay	ppm Lime	ppm Soda Ash	I cpm/ml	pH	Per Cent Activity Removed No Aid S	No Aid C	5 ppm N17* S	5 ppm N17* C
ILLITE								
0	202	45	1377	10.4	77.7	78.6	79.0	81.6
100	202	45	1377	10.3	79.8	80.1	81.9	81.1
500	202	45	1377	10.2	83.5	84.7	84.5	83.8
1000	202	45	1377	10.1	84.6	87.2	87.3	89.9
2500	202	45	1377	9.6	89.2	89.8	90.3	89.6
5000	202	45	1377	8.7	90.0	90.9	91.0	91.0
VOLCLAY								
0	202	45	1377	10.3	80.8	82.8	81.6	83.5
100	202	45	1377	10.2	83.9	86.2	85.6	85.0
500	202	45	1377	10.2	89.0	90.7	91.0	90.5
1000	202	45	1377	10.3	90.7	94.8	95.0	95.4
2500	202	45	1377	10.4	91.5	97.8	97.5	98.4
5000	202	45	1377	10.4	94.0	98.4	97.5	98.6

*After the normal mixing and settling periods, samples were taken and 5 ppm N17 was added to each jar with 3 min. rapid mix, 10 min. slow mix, and 20 min. settling before resampling.

TABLE 9

REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY AND VARIABLE DOSAGES OF LIME, SODA ASH, AND DIS-106

ppm 106	ppm Lime	ppm Soda Ash	I cpm/ml	pH	Per Cent Activity Removed	
					Settled	Centrifuged
0	117	0	1856	9.2	91.8	94.9
0.5	117	0	1856	9.2	94.0	96.1
5	117	0	1856	9.2	95.0	96.2
20	117	0	1856	9.2	95.1	95.6
0	188	35	1856	10.3	92.9	98.3
0.5	188	35	1856	10.3	96.2	98.4
5	188	35	1856	10.3	96.3	98.6
20	188	35	1856	10.3	96.8	98.6
0	188	200	1856	10.6	93.6	99.3
0.5	188	200	1856	10.6	98.2	99.4
5	188	200	1856	10.6	98.5	99.4
20	188	200	1856	10.6	98.7	99.5

TABLE 10

REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY, 202 ppm LIME, 45 ppm SODA ASH, AND VARIABLE DOSAGES OF N17

ppm N17	Order of Addition	I_0 cpm/ml	pH	Final Turbidity	Per Cent Activity Removed	
					Settled	Centrifuged
0		1150	10.5	1200	93.4	98.6
1	Aid first	1150	10.3	950	94.0	98.2
2	Aid first	1150	10.3	750	95.6	98.7
5	Aid first	1150	10.3	200	98.0	99.0
1	Aid last	1150	10.4	1000	94.8	97.6
2	Aid last	1150	10.3	800	96.0	99.0
5	Aid last	1150	10.5	500	96.9	-

TABLE 11

REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY, 202 ppm LIME, 45 ppm SODA ASH, AND VARIABLE DOSAGES OF W

W	Order of Addition	I cpm/ml	pH	Final Turbidity	Per Cent Activity Removed	
					Settled	Centrifuged
0		1150	10.5	1200	94.4	98.0
1	Aid first	1150	10.3	1200	95.6	97.4
2	Aid first	1150	10.6	1200	93.8	98.0
5	Aid first	1150	10.6	1200	97.6	97.1
1	Aid last	1150	10.4	1200	93.5	97.1
2	Aid last	1150	10.4	1200	94.0	98.0
5	Aid last	1150	10.5	1200	92.0	96.9

TABLE 12

REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY, 202 ppm LIME, 200 ppm SODA ASH, 10 ppm STABLE Sr, AND VARIABLE DOSAGES OF N17

I_o cpm/ml	pH	Per Cent Activity Removed and Turbidity											
		ppm N17											
		0		1		2		5		10		15	
		S	C	S	C	S	C	S	C	S	C	S	C
900	10.4	93.5	99.4	97.6	99.4	97.1	99.4	99.2	99.0	99.0	99.0	98.4	98.4
		(1200)		(625)		(380)		(45)		(20)		(15)	

TABLE 13

REMOVAL OF Sr^{89} FROM WELL WATER WITH 5000 ppm VOLCLAY, EXCESS LIME (402 ppm), EQUIVALENT SODA ASH (326 ppm), 10 ppm STABLE Sr, AND VARIABLE DOSAGES OF N17

I_0 cpm/ml	pH	Per Cent Activity Removed and Turbidity											
		ppm N17											
		0		1		2		5		10		15	
		S	C	S	C	S	C	S	C	S	C	S	C
915	11.6	97.6	98.1	98.1	98.4	98.3	97.5	98.2	98.4	96.8	97.4	95.0	97.5
		(325)		(140)		(62)		(11)		(13)		(21)	

TABLE 14

REMOVAL OF Pm^{147} FROM TAP WATER WITH 60 ppm ALUM OR 36 ppm FERRIC SULFATE AND VARIABLE DOSAGES OF COAGULANT AIDS

				Per Cent Activity Removed									
				ppm Aid									
			I	0		0.2		0.5		1		5	
Aid	Coagulant	pH	cpm/ml	S	C	S	C	S	C	S	C	S	C
N17	Aid + Alum	6.9	329	92.8	97.5	94.3	95.5	92.3	95.5	89.6	94.8	91.2	95.7
N17	Alum + Aid	6.9	329	92.8	97.5	91.9	96.4	91.4	95.5	89.8	95.7	89.4	94.6
N17	Aid + Iron	6.7	313	93.5	99.1	96.3	99.1	94.8	99.3	95.9	99.5	95.0	99.1
N17	Iron + Aid	6.7	313	93.5	99.1	92.8	98.7	95.6	98.5	93.7	98.7	95.9	98.2
110	Aid + Alum	7.0	776	94.2	98.3	91.5	98.2	95.6	98.7	97.1	98.7	97.2	98.7
110	Alum + Aid	7.0	776	94.2	98.3	94.6	97.7	94.2	97.1	95.1	97.9	93.9	97.2
110	Aid + Iron	7.5	776	98.8	99.6	97.8	99.6	98.8	99.5	98.5	99.3	98.3	99.5
110	Iron + Aid	7.5	776	98.8	99.6	98.6	99.6	98.3	99.8	98.0	99.2	97.1	99.3

TABLE 14 - CONTINUED

				Per Cent Activity Removed									
				ppm Aid									
				0		0.2		0.5		1		5	
Aid	Coagulant	pH	I_0 cpm/ml	S	C	S	C	S	C	S	C	S	C
W	Aid + Alum	7.5	819	97.6	98.6	97.9	98.9	98.6	99.2	98.4	99.3	96.8	98.7
W	Alum + Aid	7.5	819	97.6	98.6	97.5	98.5	97.3	98.4	95.4	97.2	92.4	95.1
W	Aid + Iron	6.6	313	-	-	96.9	98.7	97.6	98.9	97.6	98.0	96.5	98.5
W	Iron + Aid	6.6	313	-	-	96.9	98.7	94.3	98.0	95.2	98.5	95.0	96.9
WPB	Aid + Alum	7.4	819	98.1	99.1	97.1	98.9	97.8	98.9	98.0	98.9	97.3	98.6
WPB	Alum + Aid	7.4	819	98.1	99.1	97.0	99.1	97.8	98.7	97.6	99.0	97.6	98.7
WPB	Aid + Iron	7.0	843	99.2	99.8	99.2	99.3	99.4	99.9	99.2	99.8	98.1	99.8
WPB	Iron + Aid	7.0	843	99.2	99.8	98.9	99.7	98.9	99.8	98.2	99.9	98.6	99.7

TABLE 14 - CONTINUED

				Per Cent Activity Removed									
				ppm Aid									
				0		0.2		0.5		1		5	
Aid	Coagulant	pH	I_0 cpm/ml	S	C	S	C	S	C	S	C	S	C
12H	Aid + Alum	6.9	756	92.5	98.6	94.0	98.4	86.4	98.3	95.4	97.9	98.3	97.2
12H	Alum + Aid	7.0	756	92.5	98.6	92.9	97.7	93.3	96.7	91.2	95.4	93.3	96.3
12H	Aid + Iron	7.6	684	98.1	97.0	97.6	99.4	97.6	99.4	96.6	98.9	15.2	45.5
12H	Iron + Aid	7.6	684	98.1	97.0	96.9	98.4	96.0	97.9	96.5	97.2	96.2	97.2
65	Aid + Alum	7.4	962	93.1	95.7	92.4	96.6	93.9	96.5	92.3	96.1	92.9	96.8
65	Alum + Aid	7.4	962	93.1	95.7	91.3	95.1	92.8	95.0	91.6	95.8	88.9	93.4
65	Aid + Iron	7.4	962	97.0	99.4	96.5	99.0	96.8	99.2	95.5	99.4	96.5	99.2
65	Iron + Aid	7.4	962	97.0	99.4	96.4	99.2	95.8	98.9	95.7	98.9	90.7	95.2

TABLE 14 - CONTINUED

				Per Cent Activity Removed									
				ppm Aid									
				0		1		5		15		25	
Aid	Coagulant	pH	I cpm^{9}/ml	S	C	S	C	S	C	S	C	S	C
"SiO_2"	Aid + Alum	6.9-7.4	961	90.9	96.7	88.3	95.3	93.0	95.7	95.1	95.8	86.2	86.5
"SiO_2"	Alum + Aid	6.9-7.4	961	90.9	96.7	90.0	96.2	89.7	93.8	89.6	90.1	88.1	89.6
"SiO_2"	Aid + Iron	6.8-7.3	961	98.0	99.3	96.7	98.0	96.8	96.5	76.0	72.9	0	0
"SiO_2"	Iron + Aid	6.8-7.2	961	98.0	99.3	95.3	98.1	93.8	97.5	92.8	97.2	90.4	96.1

TABLE 15

REMOVAL OF Pm^{147} FROM WELL WATER WITH VARIABLE DOSAGES OF CLAYS

ppm Clay	Per Cent Activity Removed							
	Kaolinite		Fullers Earth		Illite		Volclay	
	S	C	S	C	S	C	S	C
0	60.1	93.7	55.1	94.1	56.7	95.7	34.4	94.7
50	66.1	88.2	60.7	85.2	70.2	89.6	74.8	92.5
200	77.1	91.1	80.0	94.8	83.3	94.7	82.7	92.6
500	93.1	96.4	94.6	97.8	91.5	96.7	90.8	91.8
1000	94.6	98.5	95.9	98.9	94.5	97.8	94.1	96.0
5000	98.4	99.5	98.7	99.7	97.3	99.5	99.0	99.7

TABLE 16

REMOVAL OF Pm^{147} FROM WELL WATER WITH VARIABLE DOSAGES OF LIME AND SODA ASH

ppm Lime	ppm Soda	I cpm/ml	pH	Per Cent Activity Removed	
				Settled	Centrifuged
0	0	1861	7.8	17.8	56.0
202	0	1861	9.4	92.9	98.9
202	46	1861	9.8	95.4	99.5
101	46	1861	8.6	88.7	89.4
152	46	1861	8.9	89.8	99.5
250	46	1861	10.7	89.6	99.5
302	46	1861	11.1	76.6	96.1
202	100	1861	9.9	93.7	99.1
202	200	1861	10.3	92.4	99.7
302	187	1861	11.1	91.7	99.0
404	329	1861	11.5	84.2	95.8

TABLE 17

REMOVAL OF Pm^{147} FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, AND VARIABLE DOSAGES OF COAGULANT AIDS

		Per Cent Activity Removed														
		ppm Aid														
		0			0.1			0.5			1			5		
Aid	Mix Order	S		C	S		C	S		C	S		C	S		C
106	Coagulants + Aid	95.4	(26)	99.6	94.5	(26)	99.1	88.6	(56)	98.7	88.2	(64)	99.0	91.0	(78)	97.9
106	Aid + Coagulants	95.4	(26)	99.6	92.9	(63)	99.6	93.2	(50)	99.6	88.1	(89)	99.2	98.5	(140)	99.1
N17	Coagulants + Aid	94.2	(13)	98.2	92.2	(17)	97.5	92.7	(23)	97.3	92.2	(23)	97.3	90.9	(29)	95.5
N17	Aid + Coagulants	94.2	(13)	98.2	88.7	(28)	96.9	87.4	(39)	95.5	85.9	(51)	93.0	82.8	(54)	93.4
110	Coagulants + Aid	90.7	(42)	99.5	89.2	(30)	98.4	90.3	(37)	96.9	84.6	(42)	93.8	81.4	(50)	96.9
110	Aid + Coagulants	90.7	(42)	99.5	88.4	(39)	97.4	90.0	(31)	99.3	86.6	(41)	97.4	79.1	(45)	97.2

TABLE 17 - CONTINUED

Aid	Mix Order	Per Cent Activity Removed									
		ppm Aid									
		0		0.1		0.5		1		5	
		S	C	S	C	S	C	S	C	S	C
W	Coagulants + Aid	96.0 (26)	97.2	93.6 (41)	99.5	90.5 (69)	99.0	92.3 (69)	98.8	81.8 (84)	96.3
W	Aid + Coagulants	96.0 (26)	97.2	93.6 (45)	99.5	85.6 (28)	96.2	92.8 (30)	96.0	93.1 (41)	98.2
CN	Coagulants + Aid	95.3 (16)	99.5	95.1 (14)	99.6	92.9 (19)	99.3	93.5 (25)	93.2	91.2 (32)	99.3
CN	Aid + Coagulants	93.1 (15)	99.6	82.1 (22)	99.6	91.4 (21)	99.7	94.5 (23)	90.9	90.3 (31)	98.7
WPB	Coagulants + Aid	94.8 (24)	98.1	95.3 (25)	98.6	94.1 (29)	97.8	93.3 (34)	98.1	91.7 (39)	97.4
WPB	Aid + Coagulants	94.8 (24)	98.1	94.1 (26)	97.7	91.4 (26)	97.2	90.2 (26)	97.0	87.8 (28)	86.6

TABLE 17 - CONTINUED

		Per Cent Activity Removed									
		ppm Aid									
		0		0.1		0.5		1		5	
Aid	Mix Order	S	C	S	C	S	C	S	C	S	C
12H	Coagulants + Aid	87.4 (26)	97.1	87.8 (36)	97.3	75.6 (66)	96.0	69.9 (89)	95.1	66.0 (110)	94.1
12H	Aid + Coagulants	87.4 (26)	97.1	80.0 (46)	95.4	71.2 (53)	94.0	64.1 (73)	90.1	60.9 (44)	86.6
65	Coagulants + Aid	91.3 (24)	98.4	92.0 (25)	98.4	89.8 (34)	98.6	86.4 (30)	97.3	83.3 (54)	97.1
65	Aid + Coagulants	91.3 (24)	98.4	88.7 (22)	98.0	77.7 (31)	95.1	87.4 (32)	97.3	81.0 (55)	95.6
"SiO_2"	Coagulants + Aid	94.9 (27)	99.3	94.3 (28)	99.1	94.2 (25)	98.3	96.5 (7)	99.1	98.1 (1)	98.9
"SiO_2"	Aid + Coagulants	94.9 (27)	99.3	89.8 (28)	99.4	94.2 (21)	98.3	95.8 (11)	99.5	98.1 (32)	98.7

TABLE 18

REMOVAL OF Pm^{147} FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, 500 ppm CLAY, AND VARIABLE DOSAGES OF COAGULANT AIDS

				Per Cent Activity Removed									
				ppm Aid									
				0		0.2		0.5		1		5	
Aid	Clay	I cpm/ml	pH	S	C	S	C	S	C	S	C	S	C
N17	500 ppm Kaolinite	1236	10.0	95.8 (68)	98.6	89.9 (47)	97.3	91.0 (51)	97.0	84.9 (69)	94.6	77.9 (84)	92.5
N17	500 ppm Volclay	1110	10.3	96.7 (46)	98.9	97.5 (12)	97.3	97.3 (10)	97.2	94.5 (28)	89.4	88.4 (26)	99.0
				0		0.5		1		5		10	
WPB	500 ppm Kaolinite	1236	10.3	93.6 (36)	98.1	90.5 (32)	97.0	89.4 (34)	95.1	85.6 (28)	93.8	78.8 (34)	92.0

TABLE 19

REMOVAL OF I^{131} FROM WELL WATER WITH 100 ppm ACTIVATED CARBON, CHLORINE, AND VARIABLE DOSAGES OF ALUM OR FERRIC SULFATE

ppm Alum	ppm $Fe_2(SO_4)_3$	I_0 (cpm/ml)	Final pH	Per Cent Activity Removed	
				Settled	Centrifuged
C-190-N and 0.10 ppm Cl_2					
0	0	1448	8.2	61.5	73.7
15	0	1448	8.2	74.2	73.6
30	0	1448	8.0	80.8	72.4
0	10	1448	8.1	55.5	74.7
0	20	1448	8.0	55.1	70.5
Aqua Nuchar A and 0.075 ppm Cl_2					
0	0	1704	8.1	50.7	71.8
15	0	1704	8.1	67.3	71.7
30	0	1704	7.9	65.1	71.3
0	10	1704	8.0	66.4	70.4
0	20	1704	7.9	65.9	68.3

TABLE 20

REMOVAL OF I^{131} FROM WELL WATER WITH 100 ppm AQUA NUCHAR A, CHLORINE, AND VARIABLE DOSAGES OF COAGULANT AIDS

			Per Cent Activity Removed											
			Dosages of Aids (ppm)											
			0		0.05		0.1		0.5		1		5	
Aids	ppm Cl_2	I_0 cpm/ml	S	C	S	C	S	C	S	C	S	C	S	C
N17	0.08	1780	62.1	71.7	58.4	70.7	55.5	65.1	53.7	67.1	54.5	65.4	47.1	69.2
110	0.10	1309	66.0	83.1	67.2	81.8	65.4	80.3	65.3	80.1	64.0	78.0	63.8	76.8
W	0.10	2147	67.4	80.6	62.7	80.5	62.3	80.2	63.2	78.4	63.2	79.7	65.0	80.1
CN	0.08	1455	65.3	76.3	64.4	76.7	67.1	76.9	64.6	79.4	64.8	76.1	65.1	77.4
WPB	0.10	2147	67.4	80.6	64.8	78.6	60.4	79.0	60.4	78.1	56.8	78.2	50.7	76.9
12H	0.10	1821	70.2	78.7	67.2	80.4	67.2	80.3	55.2	79.7	50.1	82.3	42.1	78.3
65	0.10	1821	70.2	78.7	66.5	80.3	64.0	80.5	60.6	78.4	51.7	77.7	25.8	77.8
			0		1		3		5		10		15	
"SiO_2"+ 30 ppm Alum	0.10	1309	66.0	83.1	79.9	81.3	80.5	80.9	79.7	80.5	77.9	80.3	76.4	78.3

TABLE 21

COAGULATION OF CONCENTRATED URANIUM SOLUTION WITH LIME AND ALUM

I (cpm/ml)	ppm Alum	ppm Lime	pH	Per Cent Activity Removed	
				Settled	Centrifuged
3.96×10^2	0	410	9.0	99.1	99.5
3.96×10^2	15	410	8.8	99.3	99.5
3.96×10^2	30	410	8.5	99.1	99.5
3.96×10^2	45	410	8.4	99.5	99.7
3.96×10^2	60	410	8.3	99.3	99.8
3.96×10^2	75	410	8.1	99.5	99.7

TABLE 22

COAGULATION OF CONCENTRATED URANIUM SOLUTION WITH LIME AND FERRIC SULFATE

Initial Activity (cpm/ml)	ppm $Fe_2(SO_4)_3$	ppm Lime	pH	Per Cent Activity Removed	
				Settled	Centrifuged
3.96×10^2	0	410	9.2	99.3	99.8
3.96×10^2	10	410	9.0	99.3	99.8
3.96×10^2	20	410	8.8	99.5	99.8
3.96×10^2	30	410	8.6	99.7	99.7
3.96×10^2	40	410	8.3	99.7	99.5
3.96×10^2	50	410	8.0	99.5	99.8

TABLE 23

REMOVAL OF URANIUM FROM WELL WATER WITH 30 ppm ALUM, KAOLINITE, AND COAGULANT AIDS

			Per Cent Activity Removed					
			Dosages of Aids (ppm)					
Aids	Kaolinite	I_o cpm/ml	0	0.05	0.1	0.5	1	5
N17		2.86	73	75	75	73	72	68
N17	500 ppm	2.86	75	73	73	73	71	71
110		2.76	67	72	75	72	77	77
110	500 ppm	2.76	75	75	76	75	77	75
W		2.16	64	72	66	67	67	64
W	500 ppm	2.16	66	65	66	65	69	66
CN		2.38	66	67	66	65	-	-
CN	500 ppm	2.38	65	67	65	67	66	67
WPB		2.72	-	70	68	70	68	70
WPB	500 ppm	2.72	75	73	74	74	77	71
12H		2.72	68	65	65	65	65	65
12H	500 ppm	2.72	71	71	70	72	65	67
65		2.22	61	62	67	62	64	66
65	500 ppm	2.22	64	57	62	64	61	66

TABLE 23 - CONTINUED

			Per Cent Activity Removed					
			Dosages of Aids (ppm)					
Aids	Kaolinite	I cpm/ml	0	0.5	1.0	5.0	10	15
"SiO_2"		2.18	56	58	58	58	58	55
"SiO_2"	500 ppm	2.18	56	-	59	55	59	56

TABLE 24

REMOVAL OF URANIUM FROM WELL WATER WITH 25 ppm FERRIC SULFATE, KAOLINITE, AND COAGULANT AIDS

			Per Cent Activity Removed					
			Dosages of Aids (ppm)					
Aids	Clay	I cpm^{9}/ml	0	0.05	0.1	0.5	1	5
N17		3.38	74	73	76	66	67	67
N17	500 ppm	3.38	76	76	73	67	70	68
110		3.22	73	73	75	75	76	70
110	500 ppm	3.22	74	75	74	76	73	73
W		3.38	74	74	73	76	71	71
W	500 ppm	3.38	74	75	74	73	74	73
CN		2.52	63	59	60	60	62	64
CN	500 ppm	2.52	63	60	58	55	61	58
WPB		3.16	71	71	72	72	71	-
WPB	500 ppm	3.16	-	72	73	73	75	75
12H		3.22	76	74	73	72	74	73
12H	500 ppm	3.22	72	71	76	76	77	73
65		2.44	65	63	63	64	62	61
65	500 ppm	2.44	65	69	68	70	68	62

TABLE 24 - CONTINUED

			Per Cent Activity Removed					
			Dosages of Aids (ppm)					
Aids	Clay	I cpm/ml	0	0.5	1	5	10	15
"SiO_2"		2.18	60	56	59	55	57	55
"SiO_2"	500 ppm	2.18	59	66	59	59	59	54

TABLE 25

REMOVAL OF URANIUM FROM WELL WATER WITH 202 ppm LIME, 46 ppm SODA ASH, KAOLINITE, AND COAGULANT AIDS

			Per Cent Activity Removed					
			Dosages of Aids (ppm)					
Aids	Clay	I cpm^9/ml	0	0.05	0.1	0.5	1	5
N17		3.76	73(73)	72(74)	69(80)	64(66)	61(71)	58(62)
N17	500 ppm	3.76	86(68)	81(80)	77(73)	66(51)	62(53)	63(53)
110		2.76	77(27)	77(28)	77(31)	77(29)	77(36)	67(54)
110	500 ppm	2.76	84(36)	86(44)	84(45)	81(46)	77(41)	74(38)
W		2.16	82(29)	82(27)	84(26)	83(13)	88(2)	89(0)
W	500 ppm	2.16	91(38)	89(29)	92(26)	88(29)	86(18)	86(3)
CN		2.38	74(41)	75(38)	73(40)	74(42)	74(47)	73(64)
CN	500 ppm	2.38	79(62)	76(66)	79(64)	79(69)	77(71)	75(105)
WPB		2.72	59(31)	58(39)	59(39)	52(56)	51(71)	45(100)
WPB	500 ppm	2.72	66(54)	61(41)	65(46)	60(71)	60(71)	56(100)
12H		2.72	76(51)	74(69)	71(74)	66(92)	70(108)	63(125)
12H	500 ppm	2.72	82(73)	79(92)	81(100)	76(98)	75(90)	69(73)
65		2.22	66(42)	74(47)	73(47)	67(53)	67(51)	67(84)
65	500 ppm	2.22	78(71)	79(71)	81(74)	74(66)	75(73)	59(90)

TABLE 25 - CONTINUED

			Per Cent Activity Removed					
			Dosages of Aids (ppm)					
Aids	Clay	I_o cpm/ml	0	1	5	10	15	20
"SiO_2"		3.04	58(18)	50(26)	50(30)	68(0)	75(1)	77(0)
"SiO_2"	500 ppm	3.04	67(56)	63(35)	63(26)	65(25)	77(3)	79(2)

TABLE 26

SUMMARY OF TURBIDITY REDUCTION WITH COAGULANT AIDS

Coagulation of Clay Alone

Aid	Clay (ppm)	Δ Turbidity	Best Aid Dosage (ppm)	Rating
N17	500 K	31-5	5	A
N17	500 K	44-11	10	B
N17	500 V	3-1	0.2	A
N17	500 V	69-7	10	A
N17	500 FE	46-1	10	A
N17	1000 FE	39-21	1	B
N17	500 I	225-17	10	B
N17	1000 I	700-80	5	B
W	500 K	66-13	1	B
W	500 V	60-18	10	B
W	500 FE	46-1	1	A
W	500 I	180-13	1	B
12H	500 V	64-3	1	A
WPB	500 K	31-5	5	A
WPB	500 V	54-3	10	A
65	500 V	64-32	10	B
110	500 V	78-3	25	A
"SiO_2"	500 K	92-900	0	U
"SiO_2"	500 V	78-1500	0	U

TABLE 26 - CONTINUED

Aid	Clay (ppm)	Δ Turbidity	Best Aid Dosage (ppm)	Rating
"SiO_2"	500 FE	53-650	0	U
"SiO_2"	500 I	180-1100	0	U

Coagulation of Added Clay with Ferric Sulfate or Alum

Aid	Coagulant ppm	Clay (ppm)	Δ Turbidity	Best Aid Dosage (ppm)	Rating
110	10 $Fe_2(SO_4)_3$	1000 FE	1-5	0	U
110	10 $Fe_2(SO_4)_3$	1000 I	38-14	1	B
W	10 $Fe_2(SO_4)_3$	1000 FE	1-4	0	U
W	10 $Fe_2(SO_4)_3$	1000 I	39-35	0.5	C
WPB	10 $Fe_2(SO_4)_3$	1000 FE	2-0	0.5	A
WPB	10 $Fe_2(SO_4)_3$	1000 I	31-14	1	B
"SiO_2"	17 Alum	1000 FE	1-0	0.5	A
"SiO_2"	17 Alum	1000 I	11-73	0	U

TABLE 26 - CONTINUED

Coagulation of Softening Sludge from Theoretical
Lime-Soda Ash Dosages

Aid	Δ Turbidity	Best Aid Dosage (ppm)	Rating
106	26-140	0	U
N17	13-54	0	U
$N17^u$	73-66	0.5	B
110	42-31	0.5	B
110^u	27-54	0	U
W	26-84	0	U
W^u	29-0	5	A
12H	26-110	0	U
$12H^u$	51-125	0	U
CN	16-14	0.1	C
CN^u	41-40	0.1	C
WPB	24-39	0	U
WPB^u	31-100	0	U
65	24-22	0.1	C
65^u	42-84	0	U
"SiO_2"	27-1	5	A
"SiO_2"	18-0	0.5-5	A

TABLE 26 - CONTINUED

Coagulation of Softening Sludge from Theoretical
Lime-Soda Ash Dosages and Added Clay

Aid	Clay (ppm)	Δ Turbidity	Best Aid Dosage (ppm)	Rating
106	1000 FE	44-14	0.5	B
106	1000 I	290-35	5	B
N17	500 K	68-47	0.2	B
N17	500 V	46-10	0.5	A
N17	5000 V	1200-200	5	B
N17[u]	500 K	68-51	0.5	B
N17[1]	5000 V	1200-15	15	B
N17[2]	5000 V	325-11	5	B
110[u]	500 K	36-46	0	U
W	5000 V	1200-1200		U
W[u]	500 K	38-3	5	A
12H[u]	500 K	73-100	0	U
CN	1000 FE	40-3	1	A
CN	1000 I	240-26	1	B
CN[u]	500 K	62-105	0	U
CN	500 I + 500 FE	87-17	1	B
WPB	500 K	36-28	1	C
WPB[u]	500 K	54-41	0.05	B
65[u]	500 K	71-66	0.5	C

TABLE 26 - CONTINUED

Aid	Clay (ppm)	Δ Turbidity	Best Aid Dosage (ppm)	Rating
"SiO$_2$"	1000 FE	39-43	0	U
"SiO$_2$"	1000 I	215-29	5	B
"SiO$_2$"^{u}	500 K	56-2	20	A
1 ppm CN +				
Variable	1000 FE	10-21	0	U
N17	1000 I	37-31	0.1	C

Ratings

A - Coagulant aid improves coagulation and final turbidity is 10 or less.

B - Coagulation is significantly improved but final turbidity is greater than 10.

C - Coagulation is slightly improved by one dosage of aid but the turbidity difference is insignificant.

U - All dosages of aid result in a higher final turbidity.

Δ Turbidity - If the rating is A, B, or C, the first number is the turbidity without any aid while the last number is the lowest final turbidity with the best aid dosage. If the rating is U, the first number is again the turbidity without any aid while the last number is the highest final turbidity with any dosage of aid used.

Superscripts

u - These samples contained 30 ppm uranyl nitrate hexahydrate.

1 - This sample contained 155 ppm excess soda ash and 10 ppm stable strontium.

2 - This sample contained 100% excess lime with equivalent soda ash and 10 ppm stable strontium.

TABLE 27

SUMMARY OF ACTIVITY REMOVAL WITH COAGULANT AIDS

Coagulation of Clay Alone

Aid	Isotope	Clay (ppm)	Δ Activity	Best Aid Dosage (ppm)	Rating
N17	Cs	1000 FE	90.4-93.4 S	0.1	B
N17	Cs	1000 I	69.4-88.4 S	1	B
N17	Sr	500 V	64.5-72.0 S	1	A
W	Sr	500 V	65.9-75.7 S	1	A
W	Sr	500 V	67.6-75.7 C	10	A
"SiO_2"	Sr	500 V	60.1-69.1 S	5	A

Coagulation with Ferric Sulfate or Alum

Aid	Isotope	Coagulant ppm	Δ Activity	Best Aid Dosage (ppm)	Rating
N17	Pm	36 $Fe_2(SO_4)_3$	93.5-96.3 S	0.2	A
N17	Pm	36 $Fe_2(SO_4)_3$	99.1-99.5 C	1	A
110	Pm	60 Alum	94.2-97.2 S	5	A
110	Pm	60 Alum	98.3-98.7 C	0.5-5	A
W	Pm	60 Alum	97.6-98.6 S	0.5	A
W	Pm	60 Alum	98.6-99.3 C	1	A

TABLE 27 - CONTINUED

Aid	Isotope	Coagulant (ppm)	Δ Activity	Best Aid Dosage (ppm)	Rating
WPB	Pm	36 $Fe_2(SO_4)_3$	99.2-99.4 S	0.5	A
WPB	Pm	36 $Fe_2(SO_4)_3$	99.8-99.9 C	0.5-1	A
12H	Pm	60 Alum	92.5-98.3 S	5	B
12H	Pm	36 $Fe_2(SO_4)_3$	97.0-98.9 C	1	B
65	Pm	60 Alum	95.7-96.8 C	5	B
"SiO_2"	Pm	60 Alum	90.9-95.1 S	15	B
110	U	30 Alum	67-77 S	1-5	-
W	U	30 Alum	64-72 S	0.05	-

Coagulation of Added Clay with Ferric Sulfate or Alum

Aid	Isotope	Coagulant (ppm)	Clay (ppm)	Δ Activity	Best Aid Dosage (ppm)	Rating
110	Cs	10 $Fe_2(SO_4)_3$	1000 I	93.5-94.8 C	0.5	A
W	Cs	10 $Fe_2(SO_4)_3$	1000 I	95.1-96.6 C	5	B
WPB	Cs	10 $Fe_2(SO_4)_3$	1000 I	91.7-93.4 S	1	A
W	Pm	36 $Fe_2(SO_4)_3$	500 FE	98.8-99.3 S	0.5	B
"SiO_2"	Pm	60 Alum	500 FE	96.3-99.1 S	0.5	B

TABLE 27 - CONTINUED

Coagulation of Softening Sludge from Theoretical Lime-Soda Ash Dosages

Aid	Isotope	Δ Activity	Best Aid Dosage (ppm)	Rating
N17	Sr	64.0-80.2 S	1	B
W	Sr	81.3-85.5 C	1	B
WPB	Sr	77.4-82.6 S	0.2	A
65	Sr	67.3-79.0 S	0.5	A
65	Sr	73.9-83.5 C	0.5	A
65[1]	Sr	92.8-94.5 C	0.5	B
106	Pm	95.4-98.5 S	5	B
W	Pm	97.2-99.5 C	0.1	B
CN	Pm	99.6-99.7 C	0.5	B
WPB	Pm	98.1-98.6 C	0.1	A
"SiO_2"	Pm	94.9-98.1 S	5	B
"SiO_2"	Pm	99.3-99.5 C	1	A
W	U	82-89 S	5	-
65	U	66-74 S	0.05	-
"SiO_2"	U	58-77 S	5	-

TABLE 27 - CONTINUED

Coagulation of Softening Sludge from Theoretical
Lime-Soda Ash Dosages and Added Clay

Aid	Isotope	Clay (ppm)	Δ Activity	Best Aid Dosage (ppm)	Rating
106	Cs	1000 FE	92.5-94.7 S	0.1	A
106	Cs	1000 I	83.2-92.9 S	0.1	A
106	Cs	1000 I	96.5-97.9 C	0.1	A
"SiO_2"	Cs	1000 I	85.6-94.6 S	5	B
CN	Cs	1000 FE	89.6-96.1 S	1-5	B
CN	Cs	1000 I	83.3-95.8 S	5	A
CN	Cs	1000 I	96.0-97.0 C	1	A
CN	Cs	500 FE, 500 I	89.4-95.6 S	0.5	A
1 ppm CN + Variable N17	Cs	1000 FE	95.0-96.7 S	5	B
106[2]	Sr	5000 V	91.8-95.1 S	20	A
106[2]	Sr	5000 V	94.9-96.2 C	5	A
106	Sr	5000 V	92.9-96.8 S	20	A
106[1]	Sr	5000 V	93.6-98.7 S	20	A
106[1]	Sr	5000 V	99.3-99.5 C	20	A
N17	Sr	5000 V	93.4-98.0 S	5	A
N17	Sr	5000 V	98.6-99.0 C	2-5	A
N17[1,3]	Sr	5000 V	93.5-99.2 S	5	B

TABLE 27 - CONTINUED

Aid	Isotope	Clay (ppm)	Δ Activity	Best Aid Dosage (ppm)	Rating
N17[3,4]	Sr	5000 V	97.6-98.3 S	2	B
W	Sr	5000 V	94.4-97.6 S	5	B
N17	Pm	500 V	96.7-97.5 S	0.2	B
"SiO_2"	U	500 K	67-79 S	5	-

Ratings

A - Coagulant aid reduces residual activity from the basic decontamination process by at least 20% in either a settled or a centrifuged sample and does not increase the resudual activity in the corresponding centrifuged or settled sample.

B - Coagulant aid reduces residual activity from the basic decontamination process by at least 20% in either a settled or a centrifuged sample but increases the residual activity in the corresponding centrifuged or settled sample.

Δ Activity

The first number is the per cent activity removed by the basic decontamination process without any aid while the last number is the highest per cent activity removed with the best aid dosage. S and C denote settled and centrifuged samples respectively.

Superscripts

1 - Theoretical lime dosage and 155-165 ppm excess soda ash used.
2 - 117 ppm lime and no soda ash used.
3 - Contains 10 ppm stable Sr.
4 - 100% excess lime and equivalent soda ash used.

APPENDIX III

FIGURES

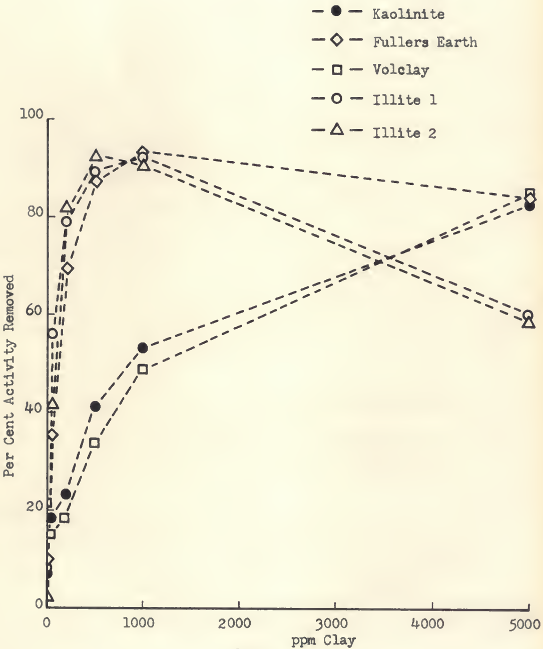

Fig. 1. - Sorption of Cs^{137} from Tap Water by Variable Dosages of Clay.

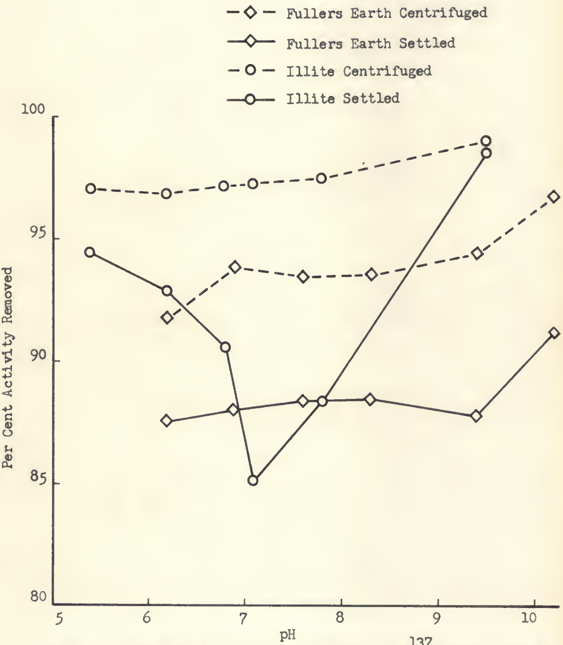

Fig. 2. - The Effect of pH on Sorption of Cs^{137} from Tap Water by 1000 ppm Fullers Earth or 1000 ppm Illite.

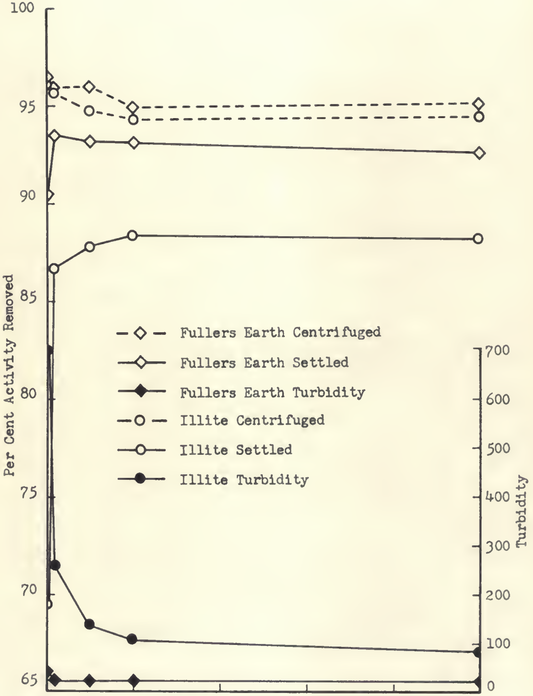

Fig. 3. - Removal of Cs^{137} from Tap Water by 1000 ppm Fullers Earth or Illite with Variable Dosages of N17.

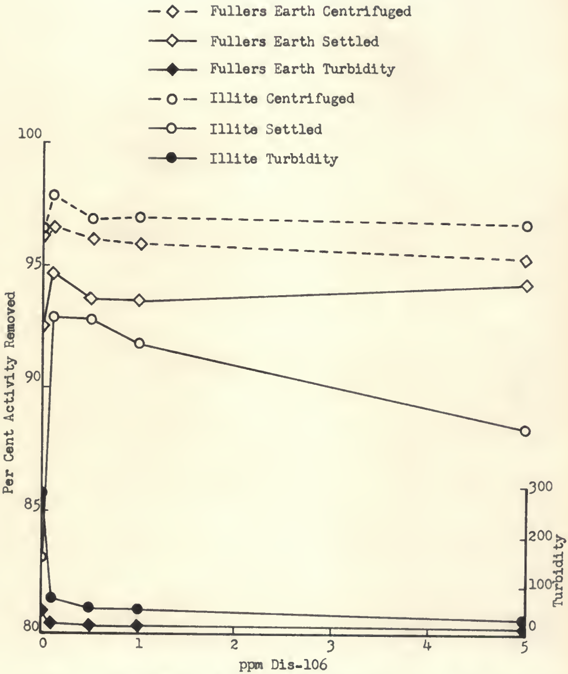

Fig. 4. - Removal of Cs^{137} from Well Water with 202 ppm Lime, 46 ppm Soda Ash, 1000 ppm Fullers Earth or Illite, and Variable Dosages of Dis-106.

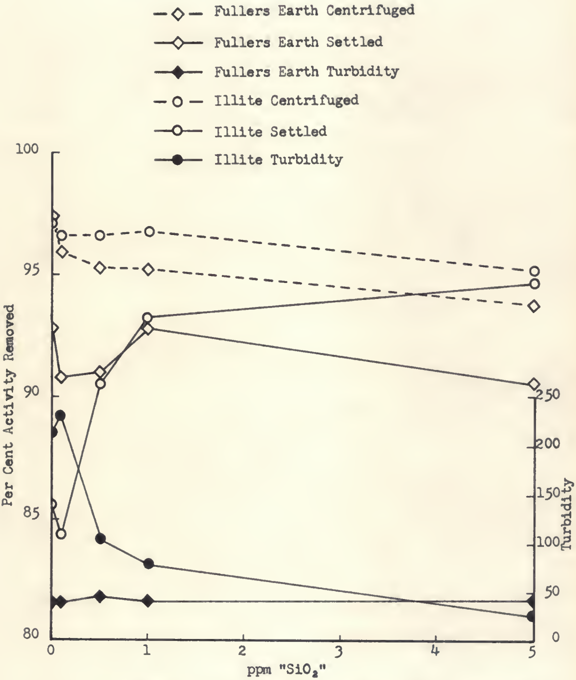

Fig. 5. - Removal of Cs^{137} from Well Water with 202 ppm Lime, 46 ppm Soda Ash, 1000 ppm Fullers Earth or Illite, and Variable Dosages of "SiO_2".

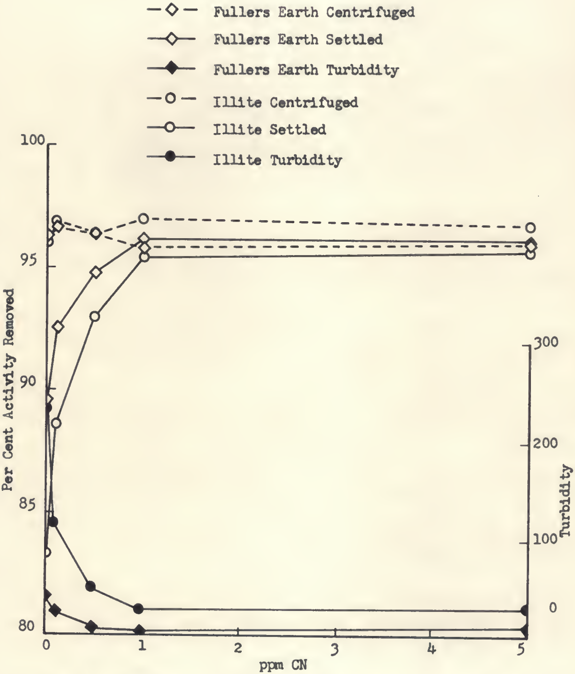

Fig. 6. - Removal of Cs^{137} from Well Water with 202 ppm Lime, 46 ppm Soda Ash, 1000 ppm Fullers Earth or Illite, and Variable Dosages of CN.

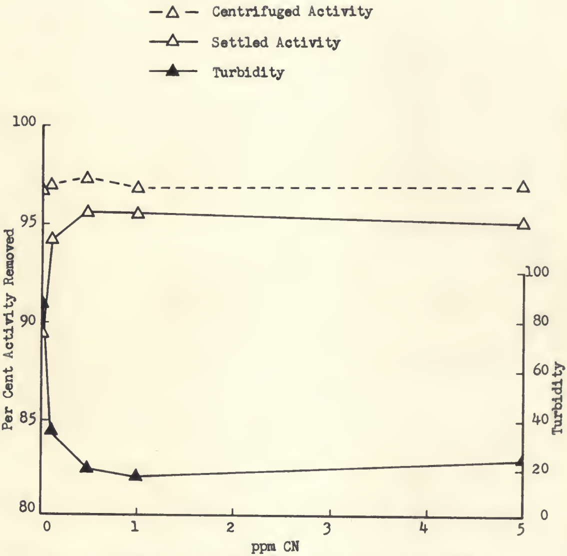

Fig. 7. - Removal of Cs^{137} from Well Water with 202 ppm Lime, 46 ppm Soda Ash, 500 ppm Fullers Earth, 500 ppm Illite, and Variable Dosages of CN.

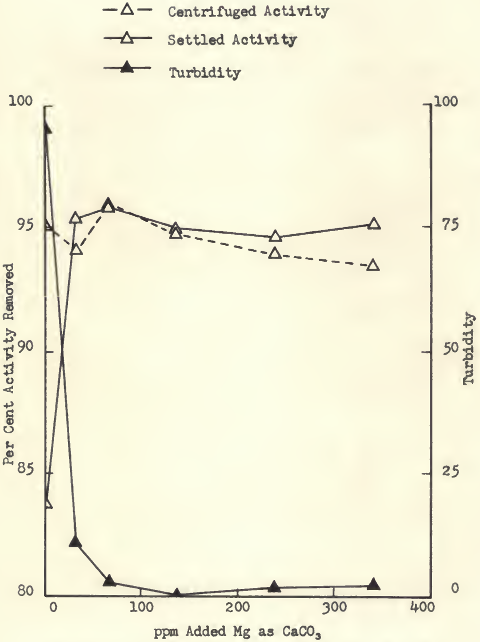

Fig. 8. - The Effect of Mg Added as $MgCl_2$ on the Removal of Cs^{137} from Well Water with Lime, Soda Ash, 500 ppm Fullers Earth, and 500 ppm Illite.

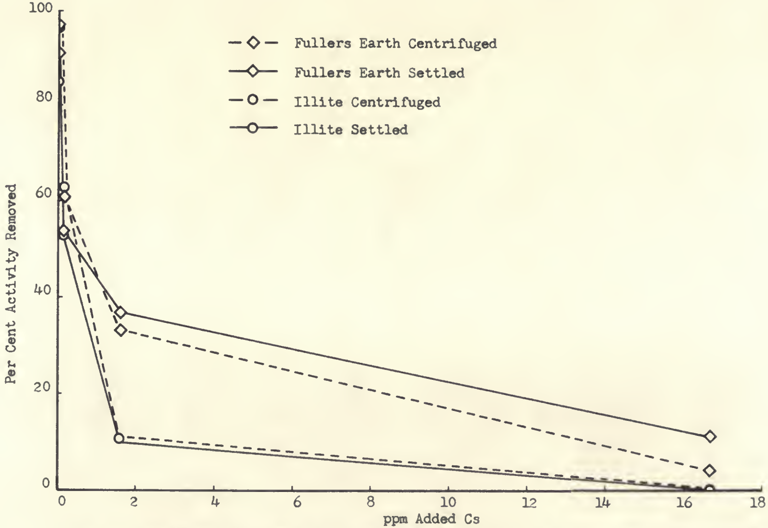

Fig. 9. - The Effect of Stable Cs on the Removal of Cs^{137} from Well Water With 202 ppm Lime, 46 ppm Soda Ash, and 1000 ppm Fullers Earth or 1000 ppm Illite.

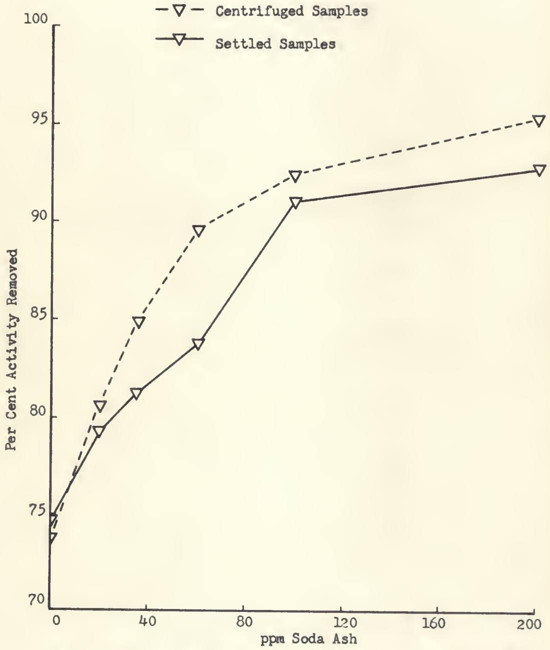

Fig. 10. - The Effect of Soda Ash Dosage on Removal of Sr^{89} from Well Water by Lime-Soda Softening.

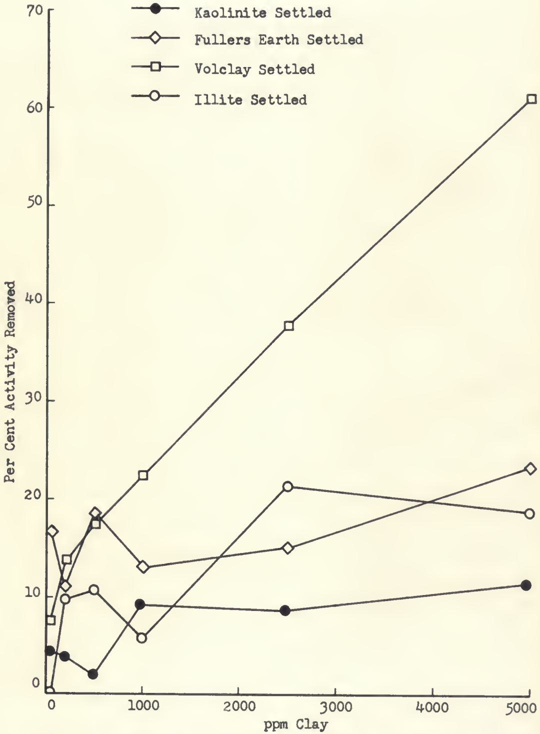

Fig. 11. - Removal of Sr^{89} from Well Water with Variable Dosages of Clay.

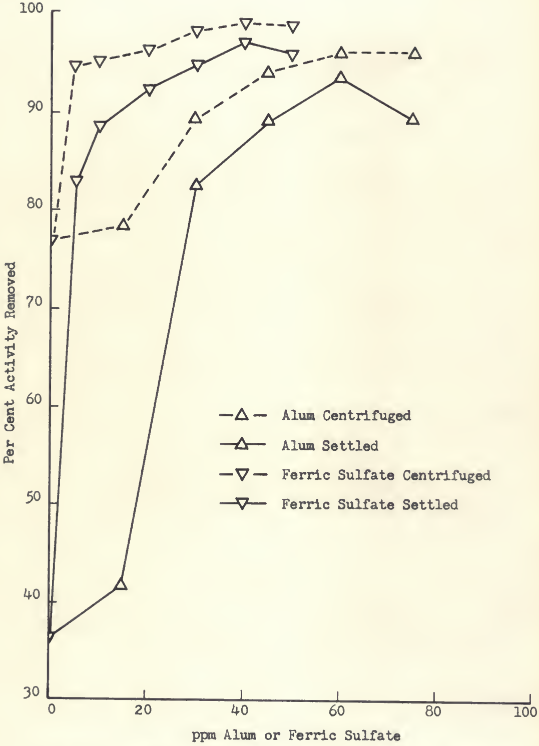

Fig. 12. - Removal of Pm^{147} from Tap Water by Coagulation with Variable Dosages of Alum or Ferric Sulfate.

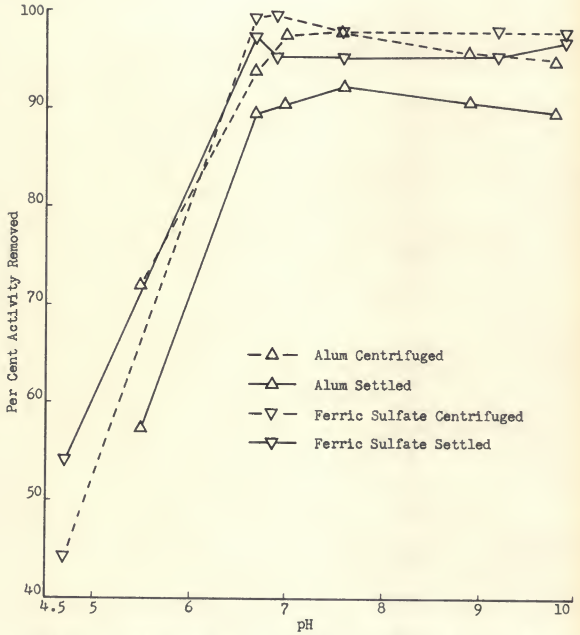

Fig. 13. - The Effect of pH on Removal of Pm^{147} from Tap Water with 60 ppm Alum or 36 ppm Ferric Sulfate.

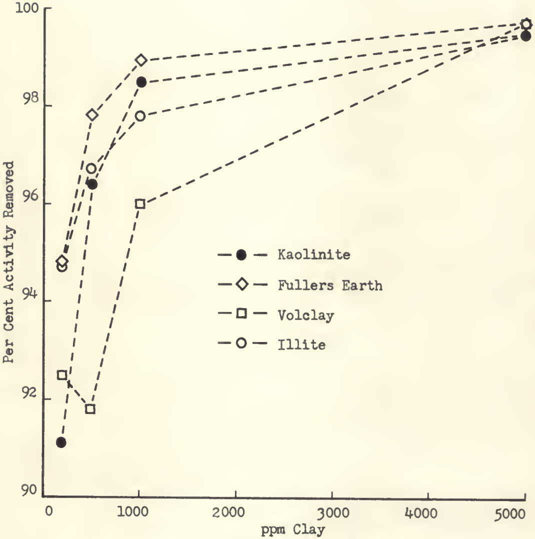

Fig. 14. - Removal of Pm^{147} from Well Water with Variable Dosages of Clays.

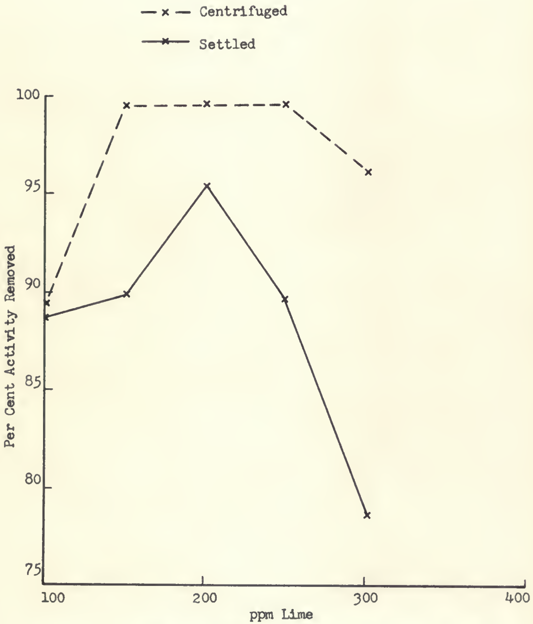

Fig. 15. - Removal of Pm^{147} from Well Water with 46 ppm Soda Ash and Variable Dosages of Lime.

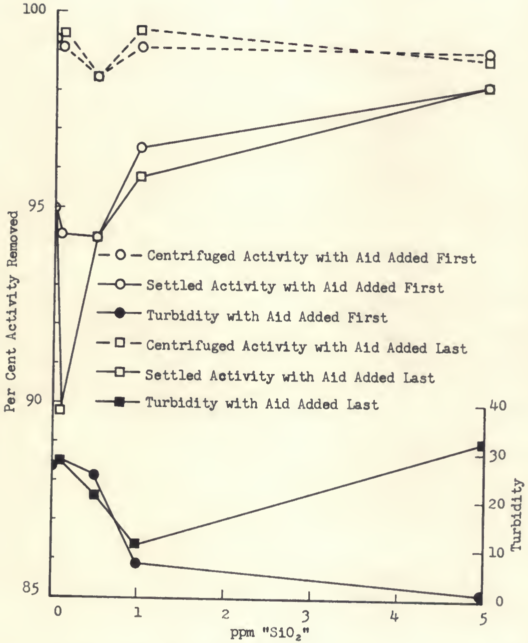

Fig. 16. - Removal of Pm^{147} from Well Water with 202 ppm Lime, 46 ppm Soda Ash, and Variable Dosages of Activated Silica.

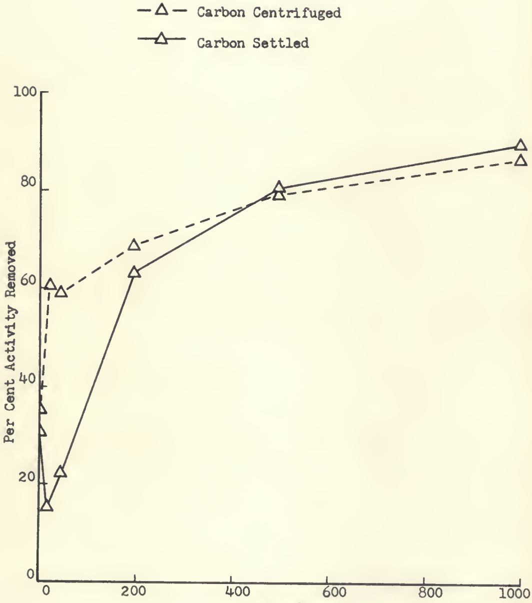

Fig. 17. - Removal of Pm^{147} from Well Water with Variable Dosages of Activated Carbon.

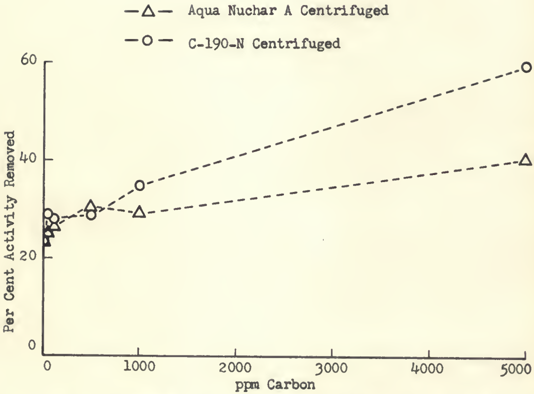

Fig. 18. - Removal of I^{131} from Well Water with Variable Dosages of Activated Carbon.

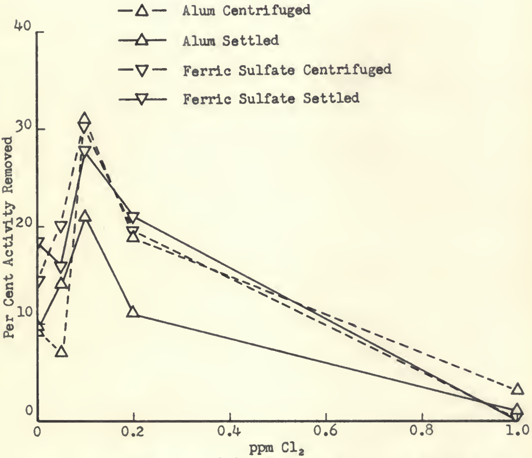

Fig. 19. - Removal of I^{131} from Well Water with Variable Dosages of Chlorine and 50 ppm Alum or 40 ppm Ferric Sulfate.

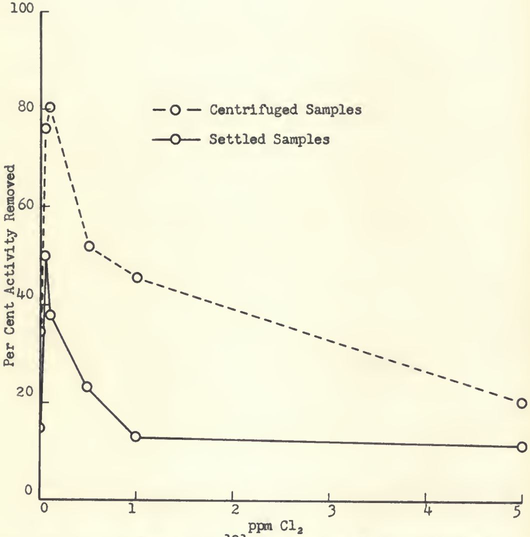

Fig. 20. - Removal of I^{131} from Well Water with Variable Dosages of Chlorine and 100 ppm C-190-N.

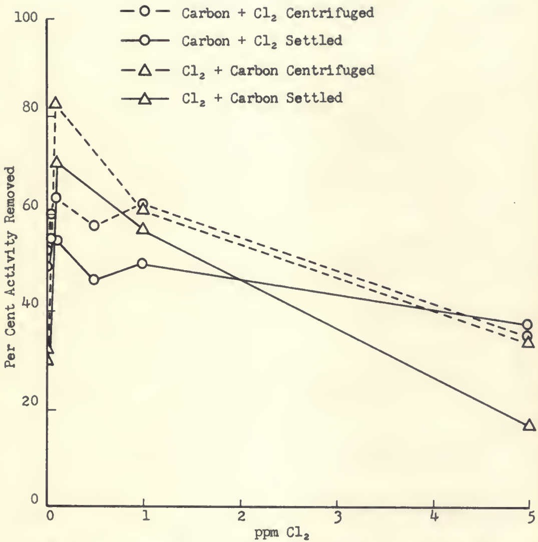

Fig. 21. - Removal of I^{131} from Well Water with Variable Dosages of Chlorine and 100 ppm Aqua Nuchar A.

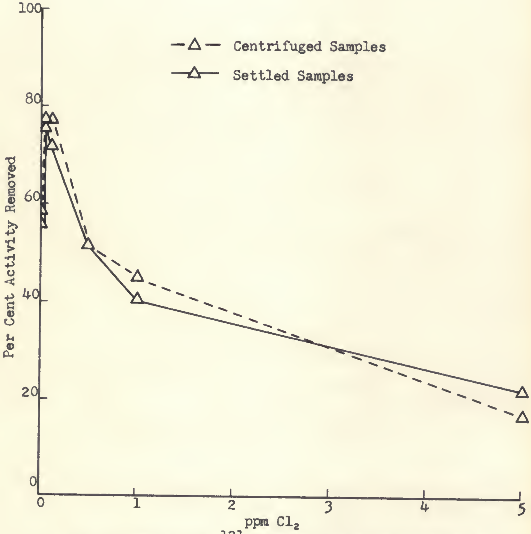

Fig. 22. - Removal of I^{131} from Well Water with Variable Dosages of Chlorine and 1000 ppm Aqua Nuchar A.

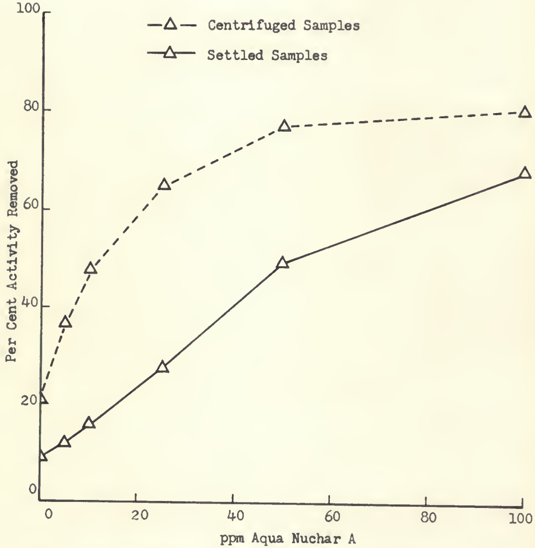

Fig. 23. - Removal of I^{131} from Well Water with 0.1 ppm Chlorine and Variable Dosages of Aqua Nuchar A.

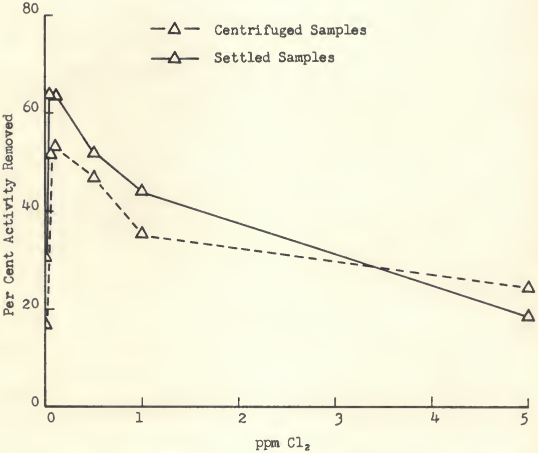

Fig. 24. - Removal of I^{131} from Well Water with 100 ppm Aqua Nuchar A, 202 ppm Lime, 46 ppm Soda Ash, and Variable Dosages of Chlorine.

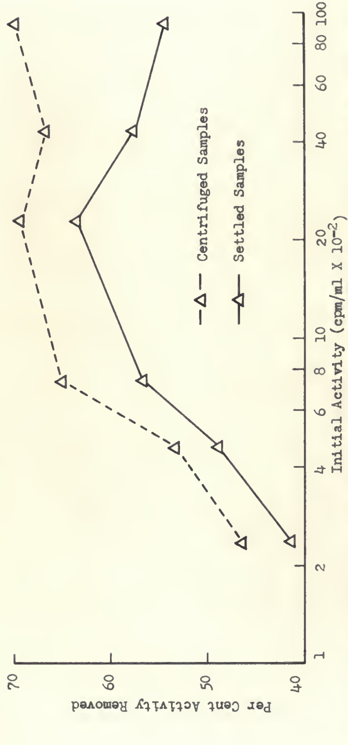

Fig. 25. - The Effect of Variable Activity on Removal of I^{131} from Well Water with 0.1 ppm Cl_2 and 100 ppm Aqua Nuchar A.

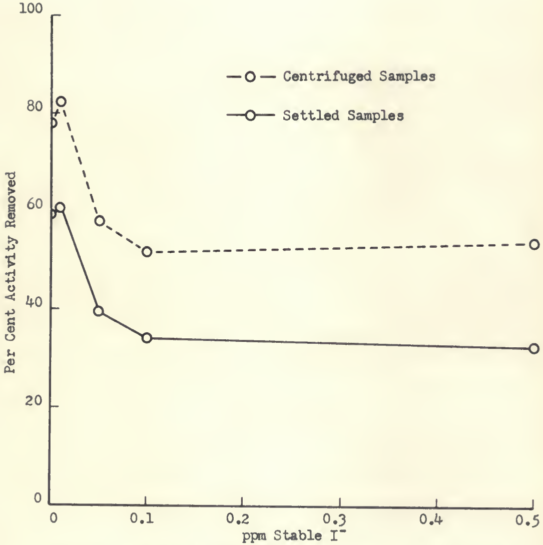

Fig. 26. - The Effect of Stable I⁻ on Removal of I^{131} from Well Water with 0.1 ppm Cl_2 and 100 ppm Aqua Nuchar A.

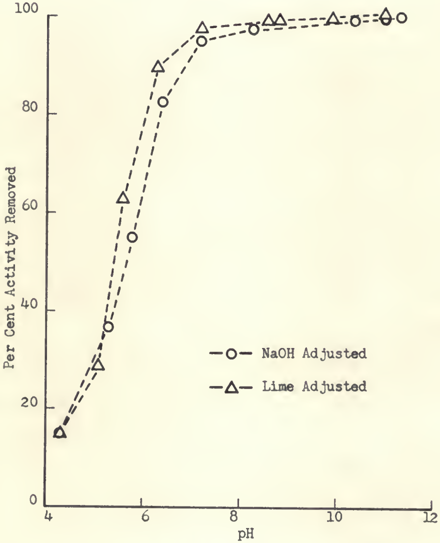

Fig. 27. - The Effect of pH on Precipitation of Uranium with Lime and Sodium Hydroxide.

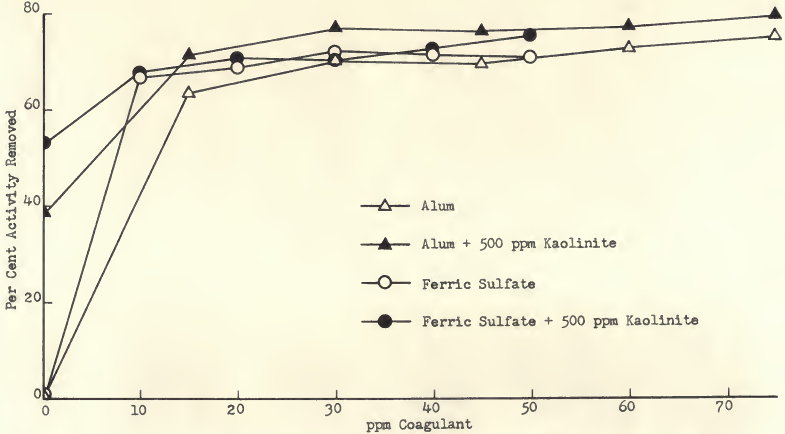

Fig. 28. - Coagulation of Dilute Uranium Solution with Kaolinite and Alum or Ferric Sulfate.

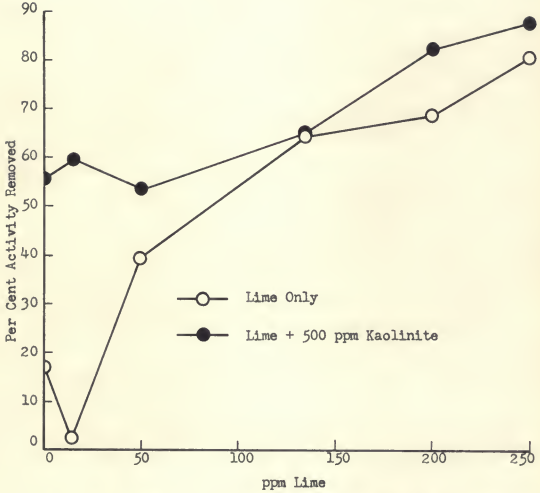

Fig. 29. - Removal of Uranium from Dilute Uranium Solution with Lime and Kaolinite.

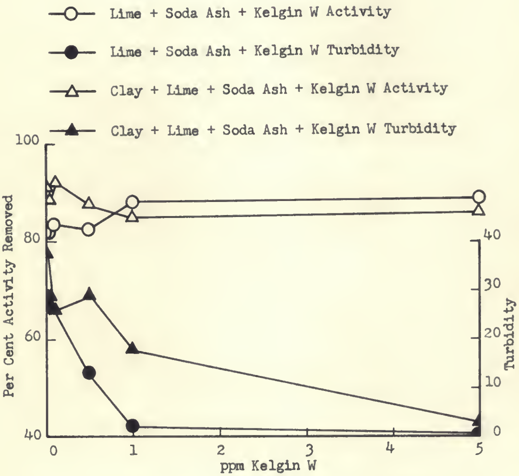

Fig. 30. - Removal of Uranium from Well Water with 202 ppm Lime, 46 ppm Soda Ash, 500 ppm Kaolinite, and Kelgin W.

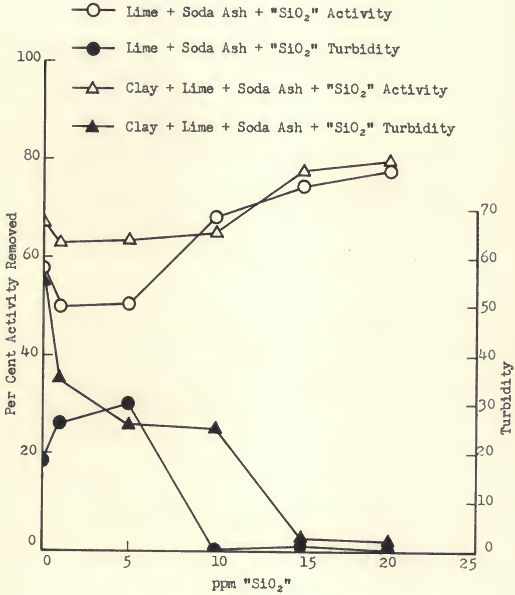

Fig. 31. - Removal of Uranium from Well Water with 202 ppm Lime, 46 ppm Soda Ash, 500 ppm Kaolinite, and Activated Silica.

LIST OF REFERENCES

1. Lindsten, D. C., Pruett, P. B., Schmitt, R. P., and Lacy, W. J. Solubility of Radioactive Bomb Debris. J. Am. Water Works Assoc., 53:256 (1961).

2. Lowe, H. N., Jr., Lindsten, D. C., Pruett, P. B., Lacy, W. J., and Kennedy, J. P. Solubility Characteristics of Radioactive Bomb Debris in Water and Evaluation of Selected Decontamination Procedures. ERDL-1569-TR (Feb., 1959).

3. Tsivoglou, E. C., Bartsch, A. F., Rushing, D. E., and Holaday, D. A. Effects of Uranium Ore Refinery Wastes on Receiving Waters. Sewage and Ind. Wastes, 30:1012 (1958).

4. Lacy, W. J. A Comparison of the Composition of Reactor Waste Solutions and Radioactive Fallout. Am. Ind. Hyg. Assoc. J., 21:334 (1960).

5. Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure. National Bureau of Standards Handbook 69 (1959).

6. Report of the Joint Program of Studies on the Decontamination of Radioactive Waters. ORNL-2557 (1959).

7. Christenson, C. W., Ettinger, M. B., Robeck, G. G., Hermann, E. R., Kohr, K. C., and Newell, J. F. Removal of Plutonium from Laboratory Wastes. Ind. Eng. Chem., 43:1509 (1951).

8. Lacy, W. J. Decontamination of Radioactively Contaminated Water by Slurrying with Clay. Ind. Eng. Chem., 46:1061 (1954).

9. McHenry, J. R., Rhodes, D. W., and Rowe, P. P. Chemical and Physical Reactions of Radioactive Liquid Wastes with Soils. TID-7517 (1955). p. 170.

10. Barker, F. B. Factors Affecting the Transport of Radioactivity by Water. J. Am. Water Works Assoc., 50:603 (1958).

11. Ehrenreich, R. Evaluation of Montmorillonite Clay for Use in Decontamination of PWR Radioactive Waste Liquors. WAPD-BT-7 (1958). p. 66.

12. Sorathesn, A., Bruscia, G., Tamura, T., and Struxness, E. G. Mineral and Sediment Affinity for Radionuclides. ORNL CF-60-6-93 (1960).

13. Lacy, W. J. Laboratory Work on Certain Aspects of the Deep Well Disposal Problem. Health Physics, 4:228 (1961).

14. Brandt, H. L. and Reisenauer, A. E. The Influence of Limestone Neutralization on the Soil Uptake of Sr^{90} from a Radioactive Waste. HW-56582 (1958).

15. Davey, P. T. and Scott, T. R. Adsorption of Uranium on Clay Minerals. Nature, 178:1195 (1956).

16. Ginell, W. S., Martin, J. J., and Hatch, L. P. Ultimate Disposal of Radioactive Wastes. Nucleonics, 12:12:14 (1954).

17. Straub, C. P., Morton, R. J., and Placak, O. R. Studies on the Removal of Radioactive Contaminants from Water. J. Am. Water Works Assoc., 43:773 (1951).

18. Eliassen, R., Kaufman, W. J., Nesbitt, J. B., and Goldman, M. I. Studies on Radioisotope Removal by Water Treatment Processes. J. Am. Water Works Assoc., 43:615 (1951).

19. Remshaw, S. J. and Wenkley, D. C. Removal of Cs^{137}, Sr^{90}, and Ru^{106} from ORNL Plant Wastes by Sorption of Various Minerals. ORNL CF-60-417 (1960).

20. Lacy, W. J. Removing Radioactive Materials from Water by Coagulation. Water and Sewage Works, 100:410 (1953).

21. Robinson, B. P. Ion Exchange Minerals and Disposal of Radioactive Wastes - A Survey of Literature. Geological Survey Water Supply Paper 1616, U. S. Govt. Printing Office, Washington, D. C. (1961).

22. Friend, A. G. Report on the Investigation of the Removal of Iodine (I^{131}) and Strontium (Sr^{89}) from Water by Ion Exchange Resins. MS Thesis, Virginia Polytechnic Institute (1952).

23. Downing, A. L., Wheatland, A. B., and Eden, G. E. Observations on the Removal of Radio-Isotopes During the Treatment of Domestic Water Supplies: II Radio-Strontium. J. Inst. Water Engineers, 7:555 (1953).

24. Swope, H. G. and Anderson, A. Cation Exchange Removal of Radioactivity from Wastes. Ind. Eng. Chem., 47:78 (1955).

25. Ayres, J. A. Treatment of Radioactive Waste by Ion Exchange. Ind. Eng. Chem., 43:1526 (1951).

26. Lacy, W. J. and Lindsten, D. C. Removal of Radioactive Contaminants from Water by Ion Exchange Slurry. Ind. Eng. Chem., 49:1725 (1957).

27. Lauderdale, R. A. and Emmons, A. H. A Method for Decontaminating Small Volumes of Radioactive Water. J. Am. Water Works Assoc., 43:327 (1951).

28. Lacy, W. J. Removal of Radioactive Material from Water by Slurrying with Powdered Metal. J. Am. Water Works Assoc., 44:824 (1952).

29. Lauderdale, R. A. A Summary of the Work of the MIT Sanitary Engineering Department on the Decontamination of Radioactive Water. Sanitary Engineering Conference at South District Filtration Plant, City of Chicago. WASH-129 (1952).

30. Newell, J. F. and Christenson, C. W. What Treatment for Radioactive Wastes? Eng. News Record, 147:19:37 (1951).

31. Pressman, M. and Lindsten, D. C. Decontamination of Water Contaminated with Plutonium. ERDL-1613-RR (1960).

32. Eden, G. E., Downing, A. L., and Wheatland, A. B. Observations on the Removal of Radio-Isotopes During Purification of Domestic Water Supplies: I Radio-Iodine. J. Inst. Water Engr., 6:511 (1952).

33. Lauderdale, R. A. Treatment of Radioactive Water by Phosphate Precipitation. Ind. Eng. Chem., 43:1538 (1951).

34. Kaufman, W. J., Nesbitt, J. B., Goldman, M. I., and Eliassen, R. The Removal of Radioactive Anions by Water Treatment. NYO-1571 (1951).

35. Straub, C. P., Morton, R. J., and Placak, O. R. Oak Ridge Reports on Water Decontamination Study. Eng. News Record, 147:7:38 (1951).

36. Burbank, N. C., Jr., Lauderdale, R. A., and Eliassen, R. A Study of the Removal of Radioactive Particulate Matter from Water by Coagulation. NYO-4440 (1955).

37. Lauderdale, R. A. Studies on the Removal of Radioisotopes from Liquid Wastes by Coagulation. ORNL-932 (1951).

38. Schulz, W. W. and McKenzie, T. R. The Removal of Cesium and Strontium from Radioactive Waste Solutions. TID-7517 (1955). p. 290.

39. Lauderdale, R. A. and Eliassen, R. The Removal of Radioactive Fall-Out from Water by Municipal and Industrial Water Treatment Plants. NYO-4441 (1956).

40. Bell, C. G., Jr., Thomas, H. A., Jr., and Rosenthal, B. L. Passage of Nuclear Detonation Debris Through Water Treatment Plants. J. Am. Water Works Assoc., 46:973 (1954).

41. Setter, L. R. and Russell, H. H. Chemical Coagulation Studies on Removal of Radioactivity in Water. J. Am. Water Works Assoc., 50:590 (1958).

42. Junkins, R. L. Removal of Radionuclides from the Pasco Supply by Conventional Treatment. J. Am. Water Works Assoc., 52:834 (1960).

43. Hoyt, W. A. The Effect of the Lime-Soda Water Softening Process on the Removal of Radioactive Strontium^{90}- Yttrium^{90}. MS Thesis, North Carolina State College (1952).

44. Cowser, K. E., and Morton, R. J. Radioactive Contaminant Removal from Waste Water. Evaluation of Performance. Proc. Am. Soc. Civil Engrs., 85:SA3:55 (1959).

45. Goodgal, S., Gloyna, E. F., and Carritt, D. E. Reduction of Radioactivity in Water. J. Am. Water Works Assoc., 46:66 (1954).

46. McCauley, R. F., Lauderdale, R. A., and Eliassen, R. A Study of the Lime-Soda Softening Process as a Method for Decontaminating Radioactive Waters. NYO-4439 (1953).

47. Alexander, G. V., Nusbaum, R. E., and MacDonald, N. S. Strontium and Calcium in Municipal Water Supplies. J. Am. Water Works Assoc., 46:643 (1954).

48. Cohen, J. M., Rourke, G. A., and Woodward, R. L. Natural and Synthetic Polyelectrolytes as Coagulant Aids. J. Am. Water Works Assoc., 50:463 (1958).

49. Katchalsky, A. Polyelectrolytes. Endeavour, 46:90 (1953).

50. Fuoss, R. M. and Sadek, H. Mutual Interaction of Polyelectrolytes. Science, 110:552 (1949).

51. Black, A. P. and Hannah, S. A. Electrophoretic Studies of Turbidity Removal by Coagulation with Aluminum Sulfate. J. Am. Water Works Assoc., 53:438 (1961).

52. Michaels, A. S. and Morelos, O. Polyelectrolyte Adsorption by Kaolinite. Ind. Eng. Chem., 47:1801 (1955).

53. Ruehrwein, R. A. and Ward, D. W. Mechanism of Clay Aggregation by Polyelectrolytes. Soil Sci., 73:485 (1952).

54. Fuoss, R. M. Polyelectrolytes. Science, 108:545 (1948).

55. Michaels, A. S. Aggregation of Suspensions by Polyelectrolytes. Ind. Eng. Chem., 46:1485 (1954).

56. Black, A. P. Basic Mechanisms of Coagulation. J. Am. Water Works Assoc., 52:492 (1960).

57. Black, A. P. and Willems, D. G. Electrophoretic Studies of Coagulation for Removal of Organic Color. J. Am. Water Works Assoc., 53:589 (1961).

58. Black, A. P. and Christman, R. F. Electrophoretic Studies of Sludge Particles Produced in Lime-Soda Softening. J. Am. Water Works Assoc., 53:737 (1961).

59. Rice, J. K. Use of Coagulant Aids. Proc. 16th Annual Water Conference, Eng. Soc. of Western Pa. (1955). p. 83.

60. Black, A. P., Ball, A. I., Black, A. L., Boudet, R. A., and Campbell, T. N. Effectiveness of Polyelectrolyte Coagulant Aids in Turbidity Removal. J. Am. Water Works Assoc., 51:247 (1959).

61. Wadsworth, M. E., and Cutler, I. B. Flocculation of Mineral Suspensions with Coprecipitated Polyelectrolytes. Mining Engr., 8:830 (1956).

62. Cowser, K. E., Tamura, T., Wyrick, H. J., Gardiner, D. A., Eschle, K. F., and Subbaratnam, T. Radioactive Waste Disposal. Low Level Waste Water Treatment. ORNL-2994 (1961). p. 1.

63. Rice, J. K. The Use of Organic Flocculants and Flocculating Aids in the Treatment of Industrial Water and Industrial Waste Water. ASTM Spec. Tech. Pub. No. 207 (1957). p. 41.

64. Johnson, C. E. Polyelectrolytes as Coagulants and Coagulation Aids. Ind. Eng. Chem., 48:1080 (1956).

65. EPK - Edgar Plastic Kaolin. Technical Data CT-108-1, Edgar Plastic Kaolin Co., Edgar, Fla.

66. Floridin, Technical Data and Product Specifications. Floridin Co., Tallahassee, Fla.

67. Separan NP 10 in Water Treatment. Form No. 125-165-58, Dow Chemical Co., Midland, Mich.

68. Nalcolyte 110. Nalco Product Bulletin A1-110, Nalco Chemical Co., Chicago, Ill.

69. Jaguar Guar Gum by Stein Hall. Stein, Hall and Co., New York, N. Y. (1956).

70. Permutit Coagulant Aid No. 65. Technical Bulletin CS-102, The Permutit Co., New York, N. Y. (1957).

71. Treatment of Raw and Waste Waters with PQ Soluble Silicates. Bulletin 52-19, Philadelphia Quartz Co., Philadelphia, Pa. (1955).

72. Standard Methods for the Examination of Water and Wastewater. Eleventh Edition., A.P.H.A., A.W.W.A., W.P.C.F., A.P.H.A. Publication Office, New York, N. Y. (1960).

73. Radioisotopes. Catalog and Price List, Oak Ridge National Laboratory, Oak Ridge, Tenn.

74. Lange, N. A. Handbook of Chemistry. Ninth Edition. Handbook Publishers, Inc., Sandusky, Ohio (1956).

BIOGRAPHICAL SKETCH

Sidney Allison Hannah was born on April 9, 1930, in Clifton Forge, Virginia. He received his early schooling at Clifton Forge public schools and graduated from there in June, 1947. In September, 1947, he enrolled at the Virginia Military Institute from which he received the degree of Bachelor of Science in Chemistry in June, 1951.

He was employed by the General Chemical Division of Allied Chemical and Dye Corporation at Claymont, Delaware, until he entered the Army in 1953. He served thirty-three months and was then employed by American Viscose Corporation at Roanoke, Virginia, in January, 1956, as a project chemist. In September, 1958, he entered the Graduate School of the University of Florida and has held the position of Research Assistant in the Department of Chemistry. He received the degree of Master of Science in June, 1960.

He is a member of the American Chemical Society, the American Water Works Association, the American Association for the Advancement of Science, Gamma Sigma Epsilon Chemical Fraternity, and Phi Kappa Phi Honorary Fraternity.

This dissertation was prepared under the direction of the chairman of the candidate's supervisory committee and has been approved by all members of that committee. It was submitted to the Dean of the College of Arts and Sciences and to the Graduate Council, and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

December 22, 1962

F W Herbert
Dean, College of Arts and Sciences

Dean, Graduate School

Supervisory Committee:

A. P. Black
Chairman

W A Bray Jr.

F. W. Geleras

H. E. Schweyer

J. M. Pearce